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A METHOD OF EFFICIENTLY CALCULATING THE  
TEMPERATURE DISTRIBUTION HISTORY IN  
STRUCTURAL ELEMENTS EXPOSED TO THE  
THERMAL RADIATION PULSE OF A NUCLEAR  
WEAPON EXPLOSION

Donald M. Wilson

Naval Ordnance Laboratory  
White Oak, Maryland

10 August 1972

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Prepared by  
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This study is part of a continuing effort to determine the susceptibility of critical shipboard topside systems to thermal radiation and thermal radiation-airblast interaction effects from nuclear weapon explosions. This report presents a method to simply obtain temperature distribution histories in system elements which are directly exposed to the thermal pulse of a nuclear weapon burst. The method has been applied to four different elements typically found in shipboard systems. Computer programs to obtain the temperature response in these elements are included.

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ROBERT WILLIAMSON II  
Captain, USN  
Commander



W. W. SCANLON  
By direction

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## INTRODUCTION

The susceptibility of shipboard systems to damage from a nuclear weapon thermal radiation pulse is determined by calculating the transient temperatures induced in simple elements of the system. Simple elements chosen are those which are the most vulnerable or whose failure is the most damaging to the system. The computation of temperature in even the most simple elements requires the use of a numerical computer program based on finite difference techniques. Such programs exist for several elements such as circular cylinders (reference (1)), flat plates (reference (2)), T-beams (reference (3)) and box beams (reference (4)). However, all of these programs require that judgement be made in choosing time and spacial increment in order that the numerical calculation be stable and accurate. Hence, experience in the use of numerical computer programs is required in order to set up and obtain accurate results from them.

This report describes an efficient, convenient and reasonably accurate method of obtaining the temperature response in selected elements exposed to the thermal radiation pulse of a nuclear weapon. The method has been summarized into simple computer programs which are much less costly to run than the numerical programs and require no previous experience in numerical analysis. The following steps were required to develop these simple programs. First a dimensional analysis is made of the element heating problem. This consists of non-dimensionalizing the heat conduction equation and its boundary conditions which include heating by the nuclear weapon thermal radiation pulse for an air burst in the lower atmosphere (reference (6)). The result is the derivation of dimensionless variables which express the temperature response in terms of a minimum number of parameters. Secondly, accurate numerical solutions are carefully obtained from a pertinent numerical computer program. Dimensionless temperature distribution histories calculated with these programs were punched on cards for selected values of the dimensionless variables which were derived in the first step. Next, rules for interpolating or extrapolating the dimensionless temperature data are derived. Finally, computer programs are written which (1) use these rules to interpolate within the dimensionless temperature arrays (2) convert the dimensionless temperatures into useful temperature histories and (3) print out all of the results in a convenient format.

This method of obtaining the temperature response can, in principle, be applied to any shipboard element. It will be illustrated in this report by applying it to the following simple elements.

- (1) Circular Cylinders whose axis of symmetry is normal to the incoming radiation
- (2) Flat plates
- (3) Circular Cylinders rotating at 6 rpm about the axis of symmetry normal to their cross sections
- (4) Thermally-Thin Elements

The application to thermally-thin elements requires a modification of the method. Here, the temperature response is given by an energy balance on the element, and the non-dimensional temperature history is simply the normalized radiant exposure history of the nuclear weapon thermal pulse. Details of doing this are given in a later section of this report.

As an aid in deciding if the solutions generated in this report will be applicable to a particular problem, the heat transfer equations and boundary conditions for the four above elements are given in Appendix . . . Also included in the appendix is a figure (Figure A-1) depicting the geometry of the elements and the positions for which temperatures can be found.

A computer program was written to obtain the temperature response of each of the above four elements which are exposed to the thermal radiation pulses of a nuclear weapon. The use of these programs will be described along with the application of the method to these elements. The computer programs are not essential to the method of obtaining the temperature response. For example, the dimensionless representation of temperature has been published in graphical form for flat plates (reference (5)) and for two-dimensional circular cylinders (reference (7)). It only remains to apply the interpolation rules which are given herein to obtain the desired temperature histories. But although these charts are easy to use, it is time consuming to compute the values of dimensionless parameters, locate the correct curve, and compute the temperature histories from their dimensionless values. Furthermore, it is frequently necessary to interpolate between curves which may be difficult when the interpolation is not linear.

The techniques developed in this report are similar to previous work done at the University of California (reference (8)). The principal difference is that in this study heating is caused by the nuclear weapon thermal radiation pulse and computer programs are used to retrieve the temperature data.

## SYMBOLS

A	absorptance
b	plate thickness
BCYL	basic description parameter for cylinders (see equation (14))
BPLT	basic description parameter for plates (see equation (8))
cp	specific heat at constant pressure
K	thermal conductivity
H	irradiance
Hm	maximum irradiance
Q	radiant exposure
Qr	absorbed radiant exposure
QT	total radiant exposure
r	cylinder radius
r*	dimensionless cylinder radius ( $r/R_o$ )
Ri	cylinder inner radius
Ri*	dimensionless cylinder inner radius ( $Ri/R_o$ )
Ro	cylinder outer radius
t	time
tm	time at which maximum irradiance of a nuclear weapon thermal pulse occurs
t*	dimensionless time ( $t/t_m$ )
T	temperature
$\bar{T}$	average temperature
T*	dimensionless temperature (see equations (5) and (9))
TI	initial temperature
X	distance into plate, measured from its surface
X*	dimensionless distance into plate ( $x/b$ )
$\alpha$	thermal diffusivity ( $K/\rho cp$ )
$\omega$	angular velocity
$\rho$	density
$\theta$	included cylinder angle, measured from the most forward point on the cylinder
$\theta^*$	dimensionless cylinder angle ( $\theta/\pi$ )

## THE DIMENSIONLESS REPRESENTATION OF THERMAL RESPONSE

A dimensionless analysis of the heat conduction equation with thermal radiation heat input from a nuclear weapon detonation was made for a plate (reference (5)) and for a circular cylinder (reference (7)). The resulting dimensionless groups will not be derived again here, instead they will be simply stated along with the assumptions required to produce them. The thermal radiation heating is given by the normalized nuclear weapon thermal radiation pulse given in reference (6) and shown in Figure 1. This curve represents the heat energy directed to any body which is directly exposed to a nuclear weapon burst. The total heating per unit area (the radiant exposure) received by the body up to time,  $t$ , is simply the integral of the thermal pulse up to that time, i.e.,

$$Q = \int_0^t H(t) dt. \quad (1)$$

Since the weapon thermal pulse is given in normalized form, the radiant exposure is more properly expressed as:

$$\frac{Q}{QT} = \frac{1}{2.6} \int_0^{t/tm} \frac{H}{Hm} d\left(\frac{t}{tm}\right) \quad (2)$$

Where  $QT = 2.6 Hmtm$  is the total radiant exposure.

Only that portion of the radiant exposure which is actually absorbed by the target element will cause its temperature to rise. The quantity of heat that is absorbed depends on the absorptance of the target surface material and on the radiative "shape factor" which describes how the target is oriented with respect to the thermal radiation source. It was assumed that the absorptance is a constant for any given target material and that the target elements are directly exposed to the weapon explosion. Hence, the amount of thermal energy absorbed is

$$Q_r = A Q \text{ for a plate} \quad (3)$$

and

$$Q_r = A Q \cos \theta \text{ for a circular cylinder} \quad (4)$$

Equation (3) or (4) represents the boundary condition for radiant heat received at the outer surfaces. Other boundary assumptions are that no heat is received at the inner surfaces and no convective or radiative cooling occurs at either surface. It was also assumed that the thermophysical properties ( $A$ ,  $K$ ,  $\rho$ ,  $c_p$  and  $\alpha$ ) do not depend on the temperature of the element. It was shown in reference (7) that these assumptions have little effect on the temperature history of shipboard elements in practical applications. Using these assumptions and boundary conditions, dimensionless variables were chosen such that a minimum number of parameters were required to define the temperature distribution history. The dimensionless groups found were the following.

(a) For plates

$$(1) \text{ Dimensionless Temperature } T^* = (T - T_I) / (AH_m b / K) \quad (5)$$

$$(2) \text{ Dimensionless Time } t^* = t / t_m \quad (6)$$

$$(3) \text{ Dimensionless Distance into Plate} \\ X^* = X / b \quad (7)$$

$$(4) \text{ Basic Description Parameter} \\ BPLT = \alpha cm / b^2 \quad (8)$$

The temperature rise of plates was given in reference (5) by plotting graphs of dimensionless temperature versus dimensionless time for 12 values of the basic description parameter. Figures were presented for three values of dimensionless distance which correspond to the surface, midplane and backface of the plate.

(b) For circular cylinders

$$(1) \text{ Dimensionless Temperature } T^* = (T - T_I) / (AH_m R_o / K) \quad (9)$$

$$(2) \text{ Dimensionless Time } t^* = t / t_m \quad (10)$$

$$(3) \text{ Dimensionless Radius into Cylinder} \\ r^* = r / R_o \quad (11)$$

$$(4) \text{ Dimensionless Inner Radius} \\ R_i^* = R_i / R_o \quad (12)$$

$$(5) \text{ Dimensionless Cylinder Angle} \\ \theta^* : \theta / \pi \quad (13)$$

$$(6) \text{ Basic Description Parameter} \\ BCYL = \alpha t_m / R_o^2 \quad (14)$$

The temperature rise of circular cylinders was given in reference (7) by plotting graphs of dimensionless temperature versus dimensionless time for ten values of the basic description parameter. Figures were presented for three values of the dimensionless radius, five values of the dimensionless inner radius, and six values of the dimensionless cylinder angle (a total of 90 figures).

A dimensional analysis similar to that made for circular cylinders could be made for rotating circular cylinders and an additional parameter(s) derived to account for rotation. However, this will not be done since the temperature histories of this report were obtained for one rotational speed only (6 rpm). Therefore, the dimensionless representation of the stationary cylinders will be used to describe the single-speed rotating cylinders discussed herein.

#### INTERPOLATION OF THE DIMENSIONLESS DATA

Dimensionless temperature histories have been computed for plates, circular cylinders and circular cylinders rotating at 6 rpm which are directly exposed to the thermal radiation pulse of a nuclear weapon. The calculations were made using the previously mentioned computer programs which are based on finite difference techniques. Accuracy of the calculations was insured by a careful choice of time and distance increments to be used in the computations. (See reference (7) for a discussion of the accuracy of numerical solutions.) A large number of computer runs were made and the temperature histories computed were converted to dimensionless values and punched on computer cards. Cards were punched for selected values of the dimensionless variables. These selected values are given in Table 1 for plates, circular cylinders and rotating circular cylinders. The dimensionless temperature data was organized such that the dimensionless temperatures are given in terms of the dimensionless time with all of the remaining dimensionless parameters varied in turn.

Since the parameter values of a given problem may not coincide with those for which a calculated solution exists, it is generally necessary to interpolate or extrapolate among those parameter values for which calculations have been made. The procedure was to find the dimensionless temperature history for only the values of dimensionless time ( $t^*$ ) and dimensionless geometric variables ( $r^*$ ,  $\theta^*$  or  $X^*$ ) which are listed in Table 1. Hence it is necessary to interpolate among the remaining dimensionless variables only (BCYL and  $Ri^*$  for the cylinders and BPLT for the plate).

Rules for the interpolation of dimensionless temperature data for cylinders were derived in reference (7). A distinction is made when the element is thermally-thick or not. An element is defined to be thermally-thick at any time if its inner surface temperature rise is less than one percent of its outer (exposed) surface temperature rise at that time. The following rules will be used for the interpolation or extrapolation of dimensionless temperature data.

## (1) Thermally-thick elements

$$(a) \text{ Cylinders} \quad T^* \sim \sqrt{BCYL} \cdot t^* \quad (15)$$

$$(b) \text{ Plates} \quad T^* \sim \sqrt{BPLT} \cdot t^* \quad (16)$$

## (2) Non thermally-thick elements

$$(a) \text{ Cylinders} \quad T^* \sim \frac{BCYL}{1 - R_i^*} \quad (17)$$

$$(b) \text{ Plates} \quad T^* \sim BPLT \cdot t^* \quad (18)$$

The above equations show that linear interpolation is used only for the case of non thermally-thick plates (see equation (18)). In dealing with thermally-thick elements, it is necessary to use square root interpolation on the values of the basic description parameter. The non thermally-thick cylinders are the most difficult to deal with since double interpolation on the parameters BCYL and  $R_i^*$  is required as specified by equation (17). Since equations (15) through (18) are only approximate representations of the behavior of the dimensionless temperature histories, the interpolation rules will yield only an approximate result. The expected accuracy in interpolating the dimensionless data is given in a later section of this report to be less than  $\pm 5$  percent for the data banks used in the computer programs of this report.

## DESCRIPTION AND USE OF THE COMPUTER PROGRAMS

The computer programs used to retrieve the temperature distribution histories require as input the material properties and dimensions of the element along with the total radiant exposure and time at which the maximum irradiance occurs for the weapon yield of interest. Also input is the dimensionless temperature data which is in the form of decks of punched cards or a magnetic tape. From this input, the dimensionless parameters are computed and interpolation or extrapolation of the dimensionless temperature data is accomplished using the previously discussed interpolation rules (see equations (15) through (18)). The dimensionless temperatures calculated are then made dimensional and subsequently printed out in a convenient format. Four computer programs have been written, one for stationary circular cylinders, one for plates, one for circular cylinders rotating at 6 rpm and one for thermally-thin elements. These are listed in Figures 2 through 5, respectively. Fortran decks of these programs and punched cards or magnetic tape of the dimensionless temperature data may be obtained from NOL. The definition of the variables that appear in the input of these programs and their units are given in Appendix B. Note that all of these variables have the same definition regardless of in which program they are used. The following is a description of each program in turn, including instructions on punching the input data cards required to run the program.

- (1) Retrieval of temperature histories in stationary circular cylinders (Program CYLDAT)

Only two or three data input cards are required to run this program. All of the stationary circular cylinder dimensionless temperature data has been placed on a magnetic tape which makes their retrieval much simpler. The variables and their format required to run the program are given in the following table

CARD	VARIABLE	FORMAT
1	XK, RHO, CP, TM, RI, RO, TI, N	7E10.4, I10
2,3	QT, ABSR, TIME(m), M = 1, N	2E10.4, 12F5.2/12F5.2
3,4	Blank if no further runs, or repeat cards 1-3 for a new run	

Figure 2 is a complete Fortran listing of this program. The choice of either two or three data input cards arises from the choice of the number (N) of dimensionless time values (TIME) desired. Note that up to 24 values of dimensionless time may be chosen from the allowable values given in Table 1. If 12 or fewer are chosen, they will be punched on card 2 and card 3 is not present. A feature of this program is that if all 24 values of dimensionless time are desired, the variable N is made zero and no values of dimensionless time need be specified on card 2. (Card 3 is omitted).

#### (2) Retrieval of temperature histories in flat plates (Program PLT1D)

The initial data input cards required to run this program are very similar to those of the previous program. A major difference in input arises because the dimensionless temperature data for plates is available on punched cards only. Hence, card decks of dimensionless temperature data must be read in before the initial two or three data input cards. The dimensionless temperature data consists of 12 decks of punched cards (15 cards per deck) which correspond to the 12 selected values of the parameter BPLT (see Table 1). In each deck, the dimensionless temperatures are punched for the 25\* selected values of dimensionless time and the five selected values of dimensionless distance into the plate (see Table 1). The input data required to run this program, including the variables and their format for the initial data cards, are given in the following table.

CARD	VARIABLES	FORMAT
1	XK, RHO, CP, TM, THICK, TI, N	6E10.4, I10
2,3	QT, ABSR, TIME (M), M = 1, N	2E10.4, 12F5.2/13F5.2
	Blank card if no further runs, or repeat above cards for a new run	

\* One extra dimensionless temperature corresponding to  $t^* = 0$  was included in the plate data.

Figure 3 is a complete Fortran listing of this program. The variable, N, may also be made zero to obtain temperatures for all of the allowable values of time as described for the previous program.

(3) Retrieval of temperature histories in circular cylinders rotating at 6 rpm (Program ROTCYL)

The use of this program is similar to that of the preceding program in that it requires two or three initial data cards followed by a deck(s) of the dimensionless temperature data. Here, there are also 12 possible decks of dimensionless temperature data corresponding to the three selected values of the parameter,  $Ri^*$ , and four selected values of the parameter BCYL (see Table 1). In each deck, the dimensionless temperatures are punched for the 24 selected values of dimensionless time, the five selected values of dimensionless radius and the six selected values of dimensionless cylinder angle (see Table 1). To set-up this program, it is first necessary to calculate the values of  $Ri^*$  and BCYL for the problem under consideration. These values must be inspected to determine if interpolation or extrapolation of the allowable values of  $Ri^*$  or BCYL is required. A variable, KK, is input to indicate which variables are to be interpolated or extrapolated. KK is chosen from the following table.

KK	MEANING
1	No interpolation or extrapolation of either parameter
2	No interpolation or extrapolation on $Ri^*$ , interpolate on BCYL
3	No interpolation or extrapolation on BCYL, interpolate or extrapolate on $Ri^*$
4	Interpolate on BCYL, interpolate on $Ri^*$
5	Interpolate on $Ri^*$ , extrapolate on BCYL
6	No interpolation or extrapolation on BCYL, extrapolate on $Ri^*$
7	Interpolate on BCYL, extrapolate on $Ri^*$

The program for stationary cylinders, previously described, also does all of these extrapolations or interpolations (except number 5) but there the correct value of KK is selected by the program itself. Two variables, I and J, are input to indicate which dimensionless temperature decks are to be used by the program. I indicates the values of BCYL and is chosen from the following table.

BCYL	.010	.025	.050	.100
I	1	2	3	4

When interpolation is required, I will correspond to the larger value of BCYL. If extrapolation beyond BCYL = .100 is required, I is set equal to four, but extrapolation below BCYL = .01 is not allowed.\*\*

\*\* Additional dimensionless data decks could be generated for this case from the numerical programs previously mentioned.

The integer J indicates the value of  $Ri^*$  and is chosen from the following table.

$Ri^*$	0.95	0.90	0.80
J	1	2	3

When interpolation is required, J will correspond to the smaller value of  $Ri^*$ . If extrapolation below  $Ri^* = 0.8$  is required, J is set equal to three, but extrapolation above  $Ri^* = 0.95$  is not allowed. The total input data required to run this program, including the variables and their format for the initial data cards, are given in the following table.

CARD	VARIABLE	FORMAT
1	XX, RHO, CP, TM, RI, RO, TI, KK, I, J, N	7E10.4, 2(I3,I2)
2,3	QT, ABSR, TIME (M), M=1, N	2E10.4, 12F5.2/12F5.2

1-4 decks of dimensionless temperature data (120 cards per deck). Blank card if no further runs, or repeat the above cards for a new run.

The dimensionless temperature decks are loaded beginning with the deck having the smallest value of I (smallest BCYL value) and largest value of J (smallest  $Ri^*$  value). Succeeding decks will have the smaller value of J and larger value of I followed by the smaller I and smaller J and finally by the larger I and smaller J (omit any of these not required). Figure 4 is a complete Fortran listing of this program. The variable, N, may also be made zero to obtain temperatures for all of the selected values of time as was done in the two previous programs.

#### (4) Retrieval of temperature histories in thermally-thin elements (Program "THNEL")

This program finds the average temperature history of a thermally-thin element, or more precisely, of an element in which no heat is internally conducted. Target elements are usually defined to be thermally-thin if there is less than a ten percent difference between the front and rear surface temperatures and thermally-thick if the rear surface temperature is less than one percent of the surface temperature. Thus, in order to use this program, it is necessary to know where internal heat conduction effects are important. Figure 6 shows the thermally-thin and the thermally-thick regions for a plate in terms of the basic description parameter, BPLT, and the dimensionless time,  $t^*$ . For plates, the temperature histories retrieved by this program are average temperature histories but these are an accurate representation of the temperature history in the thin plate region only.

Figure 7 shows the thermally-thin and thermally-thick regions of a stationary circular cylinder in terms of the basic description parameter, BCYL, and both the dimensionless time,  $t^*$ , and the dimensionless inner radius,  $Ri^*$ . Also indicated on Figure 7 are regions where angular (circumferential) conduction is important.

For cylinders, the temperature histories retrieved by this program are the average temperature only in the region where angular conduction is negligible. Thus, these temperature histories are accurate representations of the temperature history in a cylinder only in those regions shown in Figure 7 where there is no angular conduction and the cylinder is thermally-thin. In this case, the temperature history at any point on the cylinder is the retrieved value multiplied by  $\cos \theta$  where  $\theta$  is the cylinder angle measured from the most forward point on the cylinder.

The average temperature history is found by means of a simple energy balance, i.e.,

$$\bar{T} = \frac{AQ}{\rho c_p b} + T_I \quad (19)$$

The radiant exposure,  $Q$ , was found by integrating equation (2) and normalizing the result with the total radiant exposure,  $QT$ . Since  $Q/QT$  in terms of  $t^*$  is a constant function for nuclear weapons of all yields (i.e., all values of  $t_m$ ), it was stored as permanent data in the program. This function is subsequently used in the program to compute the radiant exposure and the temperature histories are calculated by use of equation (19).

Only one data input card is required to run this program. The variables and their format for this card are given in the following table.

CARD	VARIABLES	FORMAT
1	RHO, CP, TM, THICK, TI, QT, ABSR	7E10.4
2	Blank card if no further runs, or repeat card 1 for a new run	

Figure 4 is a complete Fortran listing of the program. This program provides temperature histories for all 26 selected values of dimensionless time given in Table 1. The program has been simply modified to compute the temperature histories in rotating cylinders. The modification consists of replacing the  $Q/QT$  values with values obtained by integrating equation (2) with  $H$  replaced by  $H \cos \theta$ . Here  $\theta$  is the time-varying angle between the incoming radiation and a line normal to the cylinder at its most forward point as it rotates. Figure 7 for stationary cylinders can be used as a guide in finding the region where a rotating cylinder is both thermally-thin and has negligible angular conduction. In Figure 7, the thin cylinder region increases but the negligible angular conduction region decreases as the rotation rate is increased.

Appendix C presents examples for the set-up and use of each of the computer programs described in this section.

## ACCURACY OF THE METHOD

The present method of obtaining temperature distribution histories in target elements consists primarily of solving some representative problems, storing these solutions in dimensionless forms and retrieving the solution for a given problem by interpolating the dimensionless data. The calculations for the representative problems were made by the large numerical computer programs based on finite-difference techniques. These are accurate solutions because spacial and temporal increments were carefully selected. These calculations considered elements of constant thermophysical properties ( $K$ ,  $\rho$  and  $c_p$ ) and neglected any radiation or convective cooling on the inner or outer surfaces. However, these restrictions do not seriously limit the utility of the present method, primarily because they have a negligible effect for temperature rises which occur in shipboard applications (see reference (7)). For example, aluminum alloys which are used in many structures cannot be heated to more than a few hundred degrees centigrade or they will rapidly lose much of their strength. Also, the error involved in using constant thermophysical properties can be reduced by selecting property values midway between the initial and expected maximum temperature values.

Hence, there remains only the error introduced by the interpolation rules (equations (15) - (18)). This error can only be estimated because the interpolation rules are only approximate representations of dimensionless temperature behavior. Figure 8 shows this error by comparing the results of an accurate numerical calculation of dimensionless temperature history with the result obtained by the interpolation rules. Also shown is the result of a linear interpolation of the dimensionless data. In this example, a circular cylinder having dimensionless parameter BCYL and  $Ri^*$  values of 0.075 and 0.85, was analyzed. These values were chosen to represent a "worst case" for interpolation because; (1) interpolation on both dimensionless parameters is required and (2) there are relatively large differences in dimensionless temperature values between the selected values of the dimensionless parameters which are used for interpolation. Figure 8 shows that the interpolated result is within approximately two percent of the numerical calculation. Also the straight-forward linear interpolation is within approximately five percent of the numerical result. The reason that even the linear interpolation provides such good results is that the dimensionless data provided is sufficiently plentiful that only a small error is possible in the interpolations. Based on this example and other examples given in reference (7), it is concluded that the average deviation in temperature history in using the present interpolation method is less than  $\pm 5$  percent when compared with an accurate numerical calculation.

#### SUMMARY AND CONCLUSIONS

This report has presented a method of easily obtaining the temperature distribution history in some simple elements which have been directly exposed to the thermal radiation pulse of a nuclear weapon. Although this method requires the use of computer programs, these programs are much easier to set-up and run than the numerical programs which compute temperature distribution histories. Also, these simpler programs do not require that judgments be made in choosing input variable values. Furthermore, the simpler programs always require much less computer time to produce answers. (Typical run time is less than ten seconds per problem on the CDC 6400 computer.)

The main restrictions on the present method are that convective or radiative cooling is not accounted for and that the thermophysical properties are constant. These restrictions do not seriously effect the results of this method provided that the temperature rises generated are limited to a few hundred degrees centigrade. Since many shipboard structural elements are constructed of aluminum alloys which are only useful in this temperature range, the restrictions do not seriously limit the application of the method. The present computer programs are restricted to the range of dimensionless parameters shown in Table 1. This is not a serious limitation because a wide range of weapon yields, radiant exposures and element sizes are included in the given range of dimensionless parameters. This limitation can be remedied by providing additional dimensionless temperature data for a wider range of dimensionless parameters. Also, extrapolation of the data is allowed but must be performed with care to avoid error. The method of this report therefore provides a reliable, inexpensive and reasonably accurate way of obtaining the temperature distribution history of many practical shipboard structural elements which have been directly exposed to the thermal radiation pulse of a nuclear weapon detonation.

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- (8) Ishimoto, T., "Analytical Studies of Aircraft Structures Exposed to Transient External Heating - Summary Report of Thermal Response Studies," WADC Technical Report 57-373, June 1958

TABLE 1. VALUES OF THE DIMENSIONLESS VARIABLES FOR WHICH DIMENSIONLESS TEMPERATURES ARE STORED.

$r^*$	CYLINDERS				ROTATING CYLINDERS				PLATES		THIN ELEMENTS $r^*$
	PAR 1	$Rg^*$	$r'$	$\theta$	PAR 1	$Rg^*$	$r'$	$\theta$	PAR 2	$X^*$	
0.50	0.0001	0.0	$Rg^*$	0	0.01	0.8	$Rg^*$	0	0.01	0	0.0
0.75	0.00025	0.4	$Rg^* + 1/4 (1-Rg^*)$	$\pi/6$	0.025	0.9	$Rg^* + 1/4 (1-Rg^*)$	$\pi/6$	0.02	0.25	0.50
1.00	0.0005	0.6	$Rg^* + 1/2 (1-Rg^*)$	$\pi/3$	0.050	0.95	$Rg^* + 1/2 (1-Rg^*)$	$\pi/3$	0.05	0.50	0.75
1.25	0.0010	0.8	$Rg^* + 3/4 (1-Rg^*)$	$\pi/2$	0.000		$Rg^* + 3/4 (1-Rg^*)$	$\pi/2$	0.10	0.75	1.00
1.40	0.0020	0.9	1.0	$3\pi/4$			1.0	$2\pi/3$	0.20	1.00	1.20
1.60	0.0050			$\pi$				$5\pi/6$	0.50		1.40
1.80	0.010							$\pi$	1.0		1.60
2.00	0.025							$7\pi/6$	2.0		1.80
2.20	0.050							$4\pi/3$	5.0		2.00
2.50	0.100							$3\pi/2$	10.0		2.20
2.80								$5\pi/3$	20.0		2.50
3.25								$11\pi/6$			2.80
4.0											3.25
5.0											4.0
6.0											5.0
7.0											6.0
8.0											7.0
9.0											8.0
10.0											9.0
11.0											10.0
12.0											12.5
14.0											15.0
16.0											20.0
20.0											30.0
											40.0
											50.0

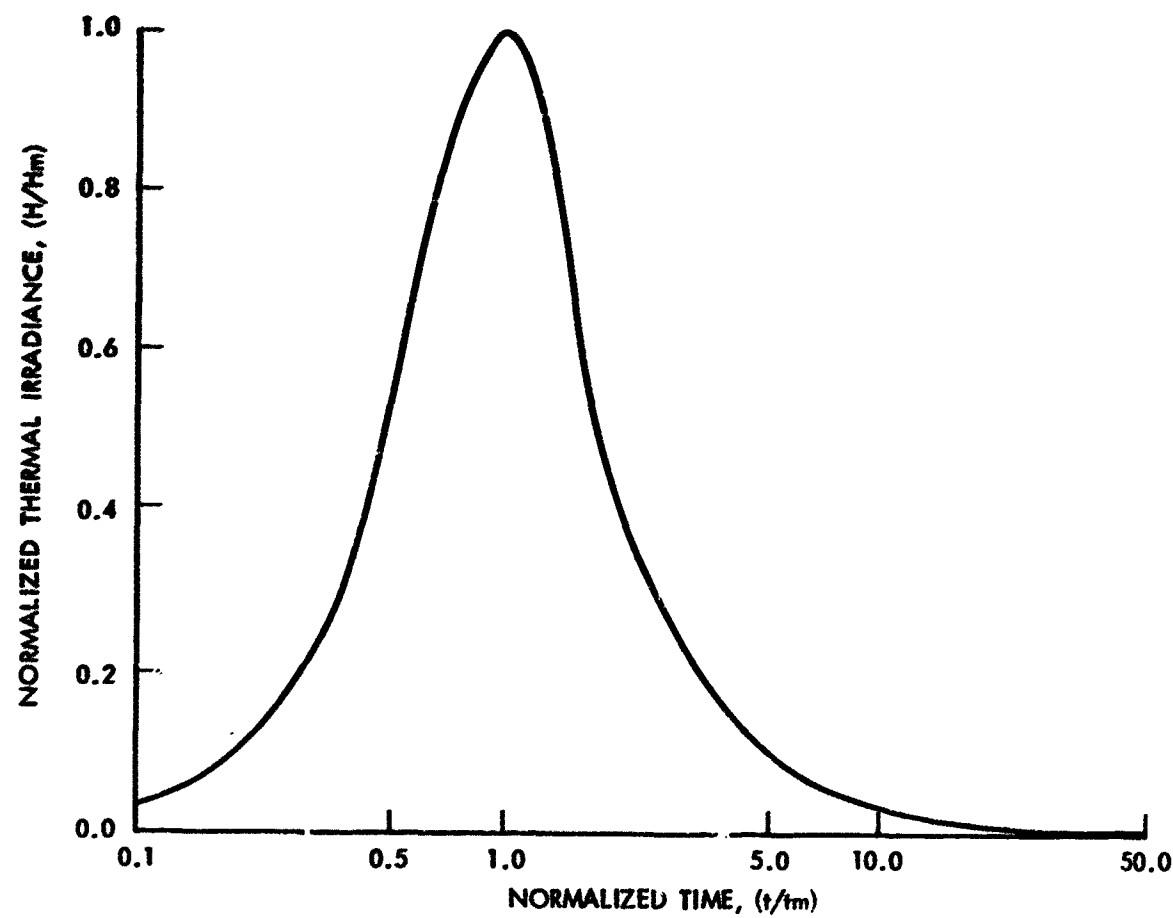


FIG. 1 NORMALIZED NUCLEAR WEAPON THERMAL RADIATION PULSE

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```

PROGRAM CYLDAT(INPUT,TAPE1,OUTPUT)
DIMENSION X(10),Y(5),W(8),Z(24),R(5),C(24,8,5),D(24,8,5),E(24,8,5)
1 .TIME(24),TEMP1(5),TEMP2(5),F(24,8,5)
DATA X/.0001,.00025,.0005,.001,.002,.005,.010,.025,.050,.100/
DATA Y/0.9,0.8,0.6,0.4,0.0/
DATA W/0.0,15.0,30.0,45.0,60.0,90.0,135.0,180.0/
DATA Z/0.5,0.75,1.0,1.2,1.4,1.6,1.8,2.0,2.2,2.5,2.8,3.25,4.00,5.0,
+6.0,7.0,8.0,9.0,10.0,11.0,12.0,14.0,16.0,20.0/
1 READ 1001,XK,RHO,CP,TM,RI,RO,TI,N
1001 FORMAT(7F10.4,I10)
    IF(N.EQ.0)GO TO 2
11 IF(XK) 120,120,9
    9 READ 1002,QT,ABSR,(TIME(M),M=1,N)
1002 FORMAT(2E12.4,10F5.2/15F5.2)
502 FORMAT(1H0,2X,56H DIMENSIONLESS TEMPERATURES FOR A DIMENSIONLESS T
    LIME OF ,F5.2,30X,6H TIME=,F6.3,7HSECONDS)
503 FORMAT(1H0,11H, CYL ANGLE=,F4.0,3HDEG,3X,5HT* =,5F7.4,5X,10HCYL AN
    1GLE=,F4.0,3HDEG,2X,5HT* =,5F7.4)
504 FORMAT(1H ,21X,5HR/RO=,5F7.4,24X,5HR/RO=,5F7.4)
505 FORMAT(1H ,21X,5HT(F)=,5F7.1,24X,5HT(F)=,5F7.1)
    GO TO 4
2 IF(XK) 120,120,7
7 READ 1002,QT,ABSR
    DO 6 M=1,24
6 TIME(M)=Z(M)
    N1=24
4 ALPHA=XK/(RHO*CP)
    A=ALPHA*TM/RO*RO)
    B=RI/RO
    PRINT 401,A,B
401 FORMAT(1H1,31H BASIC DIMENSIONLESS PARAMETERS,20X,5HBCYL=,F7.6,
    15X,6HRI/RO=,F4.3)
    PRINT 402,XK,RHO,CP
402 FORMAT(1H, 28H MATERIAL THERMAL PROPERTIES,4X,21HTHERMAL CONDUCTIV
    IITY=,F6.3,12HCAL/SEC-CM-C,4X,8HDENSITY=,F5.2,7HGMS/CM3,4X,14HSPECI
    2FIC HEAT=,F4.3,8HCAL/GM-C)
    PRINT 403,TM,QT
403 FORMAT(1H ,31H WEAPON THERMAL CHARACTERISTICS,10X,23HTIME TO MAX I
    1RADDIANCE=,F7.4,7HSECONDS,9X,23HTOTAL RADIANT EXPOSURE=,F8.2,7HCAL
    2/CM2)
    PRINT 404,RI,RO,TI
404 FORMAT(1H ,27H,13HINNER RADIUS=,F6.3,11HCENTIMETERS,4X,13HOUTER RA
    IDIUS=,F6.3,11HCENTIMETERS,4X,20HINITIAL TEMPERATURE=,F5.1,5HDEG-C)
    HM=QT/(2.60*TM)
    DEM=ABSR*HM*RO/XK
    R(1)=B
    S=(1.0-B)/4.0
    DO 3 K=2,5
    K1=K-1
3 R(K)=R(K1)+S
    KK=0

```

Figure 2. Computer Program to Obtain the Temperature History Distribution in Circular Cylinders

```

TOLXI=0.00009
TOLXE=0.11
TOLY=0.905
IF(A.LE.TOLXI.OR.A.GE.TOLXE)KK=KK+1
IF (B.GE.TOLY)KK=KK+2
IF(KK.GE.1)KK=KK+3
5 DO 10 I=1,10
TOLL=0.9*X(I)
IF(A-TOLL) 15,15,8
8 TOL2=1.1*X(I)
IF(A-TOL2) 15,15,10
10 CONTINUE
15 DO 20 J=1,5
TOLL=0.995*Y(J)
IF(B-TOLL) 18,24,24
18 TOL2=1.005*Y(J)
IF(B-TOL2) 20,24,24
20 CONTINUE
24 IF(KK) 25,25,40
25 TOLXI=0.9*X(I)
TOLXE=1.1*X(I)
IF(A.LE.TOLXI.OR.A.GE.TOLXE)KK=KK+1
TOLYI=0.996*Y(J)-0.001
TOLYE=1.004*Y(J)+0.001
IF(B.LE.TOLYI.OR.B.GE.TOLYE)KK=KK+2
40 KK=KK+1
IF(KK.LE.4)GO TO 45
J=2
KK=KK+1
DO 46 KJ=1,10
TOLL=0.9*X(KJ)
TOL2=1.1*X(KJ)
IF(A.GE.TOLI.AND.A.LE.TOL2)KK=KK-1
46 CONTINUE
45 GO TO 950,55,70,60,70,70,60)KK
50 N=10*(J-1)+I
DO 52 L=1,N
52 READ(1) (((E(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
GO TO 88
55 N=10*(J-1)+I
NN=N-1
DO 56 L=1,NN
56 READ(1) (((C(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
READ(1) (((D(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
GO TO 88
60 N=10*(J-2)+1
NN=N-1
DO 65 L=1,NN
65 READ(1) (((C(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
READ(1) (((D(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
GO TO 80
70 N=10*(J-2)+1
DO 75 L=1,N

```

```

75 READ(1) (((C(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
    NN=N+1
    N=N+10
    DO 77 L=NN,N
77 READ(1) (((E(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
    GO TO 88
80 NN=N+1
    N=N+9
    DO 85 L=NN,N
85 READ(1) (((E(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
    READ(1) (((F(K1,K2,K3),K1=1,24),K2=1,8),K3=1,5)
88 II=1
    DO 110 L=1,24
        IF(TIME(II)-Z(L)) 90,90,110
90 GO TO {108,91,98,98,91,98,98}KK
91 IF(C(L,1,1).GE.0.01*C(L,1,5)) GO TO 92
    FRAC=(SQRT(A)-SQRT(X(I-1)))/(SQRT(X(I))-X(I-1)))
    GO TO 93
92 FRAC=(A-X(I-1))/(X(I)-X(I-1))
93 J1=L
    DO 94 J2=1,8
    DO 94 J3=1,5
94 E(J1,J2,J3)=C(J1,J2,J3)+FRAC*(D(J1,J2,J3)-C(J1,J2,J3))
    GO TO 108
98 IF(C(L,1,1),LE,0.01.*C(L,1,5))GO TO 96
    F1=1.0/(1.0-Y(J))
    JK=J-1
    F2=1.0/(1.0-Y(JK))
    FB=1.0/(1.0-B)
    FRAC=(FB-F1)/(F2-F1)
    J1=L
    DO 99 J2=1,8
    DO 99 J3=1,5
99 E(J1,J2,J3)=E(J1,J2,J3)+FRAC*(C(J1,J2,J3)-E(J1,J2,J3))
    R(1)=B
    S=(1.0-B)/4.0
    DO 33 JI=2,5
33 R(JI)=R(JI-1)+S
    IF(KK-4) 35,100,35
35 IF(KK-7) 108,100,108
96 S=(1.0-Y(J))/4.0
    R(1)=Y(J)
    DO 97 JI=2,5
97 R(JI)=R(JI-1)+S
    R(1)=B
    IF(KK-4) 108,100,100
100 IF(D(L,1,1).LE.0.01*D(L,1,5))GO TO 102
    J1=L
    DO 101 J2=1,8
    DO 101 J3=1,5
101 F(J1,J2,J3)=F(J1,J2,J3)+FRAC*(D(J1,J2,J3)-F(J1,J2,J3))
102 IF(E(L,1,1).GE.0.01*E(L,1,5)) GO TO 103
    FRAC=(SQRT(A)-SQRT(X(I-1)))/(SQRT(X(I))-SQRT(X(I-1)))
    GO TO 104

```

```
103 FRAC=(A-X(I-1))/(X(I)-X(I-1))
104 J1=L
    DO 105 J2=1,8
    DO 105 J3=1,5
105 E(J1,J2,J3)=F(J1,J2,J3)+FRAC*(F(J1,J2,J3)-E(J1,J2,J3))
108 RTIM=TM*Z(L)
    PRINT 502,Z(L),RTIM
M=1
DO109 IL=1,4
M1=M+1
PRINT 503,W(M),(E(L,M,K),K=1,5),W(M1),(E(L,M1,K),K=1,5)
DO111 K=1,5
TEMP1(K)=E(L,M,K)*DEM+TI
111 TEMP2(K)=E(L,M1,K)*DEM+TI
PRINT 505,(TEMP1(K),K=1,5),(TEMP2(K),K=1,5)
PRINT 504,(R(K),K=1,5),(R(K),K=1,5)
M=M+2
109 CONTINUE
II=II+1
IF(II-N1) 110,110,115
110 CONTINUE
115 REWIND 1
GO TO 1
120 CONTINUE
STOP
END
```

```

PROGRAM PLTID(INPUT,OUTPUT)
DIMENSION X(12),Z(25),TIME(25),B(5),TEMP(5),C(25,5),D(25,5),
1E(25,5),F(25,5),G(25,5),P(25,5),R(25,5),S(25,5),T(25,5)
2U(25,5),V(25,5),W(25,5),Y(25,5)
DATA X/.01,.02,.05,.10,.20,.50,1.0,2.0,5.0,10.0,20.0,50.0/
DATA Z/0.0,0.5,0.75,1.0,1.2,1.4,1.6,1.8,2.0,2.2,2.5,2.8,3.25,4.0,5
+.0,6.0,7.0,8.0,9.0,10.0,11.0,12.0,14.0,16.0,20.0/
READ 103,((E(K1,K2),K1=1,25),K2=1,5)
READ 103,((F(K1,K2),K1=1,25),K2=1,5)
READ 103,((G(K1,K2),K1=1,25),K2=1,5)
READ 103,((H(K1,K2),K1=1,25),K2=1,5)
READ 103,((P(K1,K2),K1=1,25),K2=1,5)
READ 103,((R(K1,K2),K1=1,25),K2=1,5)
READ 103,((S(K1,K2),K1=1,25),K2=1,5)
READ 103,((T(K1,K2),K1=1,25),K2=1,5)
READ 103,((U(K1,K2),K1=1,25),K2=1,5)
READ 103,((V(K1,K2),K1=1,25),K2=1,5)
READ 103,((W(K1,K2),K1=1,25),K2=1,5)
READ 103,((Y(K1,K2),K1=1,25),K2=1,5)
1 READ 101,XK,RHO,CP,TM,THICK,TI,N
101 FORMAT(6E10.4,I10)
103 FORMAT(10F8.5/10F8.5/5F8.5)
IF (N.EQ.0)GO TO 2
IF (XK) 100,100,99
99 READ 102,QT,ABSR,(TIME(M),M=1,N)
102 FORMAT(2E10.4,12F5.2/13F5.2)
GO TO 5
2 IF (XK) 100,100,7
7 READ 102,QT,ABSR
DO 4 M=1,25
4 TIME(M)=Z(M)
5 ALPHA=XK/(RHO*CP)
A=ALPHA*TM/(THICK*THICK)
PRINT 401,A,THICK
401 FORMAT(1H1,36H BASIC DIMENSIONLESS PARAMETER BPLT=,F8.5,32X,16HPLA
1TE THICKNESS=,F6.3,11HCENTIMETERS)
PRINT 402,XK,RHO,CP
402 FORMAT(1H ,28H MATERIAL THERMAL PROPERTIES,4X,21HTHERMAL CONDUCTIV
1ITY=,F6.3,12HCAL/SEC-CM-C,4X,8HDENSITY=,F5.2,7HGMS/CM3,4X,14HSPECI
2FIC HEAT=,F4.3,8HCAL/GM-C)
PRINT 403, TM, QT
403 FORMAT(1H,31H WEAPON THERMAL CHARACTERISTICS,12X,23HTIME TO MAX I
1RRADIANCE=,F7.4,7HSECONDS,9X,23HTOTAL RADIANT EXPOSURE=,F8.2,7HCAL
2/CM2)
HM=QT/(2.6*TM)
DEM=ABSR*HM*THICK/XK
B(1)=0.0
DO 6 M=2,5
M1=M-1
6 B(M)=B(M)+THICK/4.0

```

Figure 3. Computer Program to Obtain the Temperature Distribution History in Plates

```

LJ=1
DO 9 J=1,12
I=J
IF(A-X(J)) 10,10,9
9 CONTINUE
I=13
10 GO TO(51,52,53,54,55,56,57,58,59,70,71,72,73)I
51 DO 61 M=1,25
    DO 61 N=1,5
    C(M,N)=E(M,N)
    LL=0
    GO TO 90
52 DO 62 M=1,25
    DO 62 N=1,5
    C(M,N)=E(M,N)
    62 D(M,N)=F(M,N)
    GO TO 90
53 DO 63 M=1,25
    DO 63 N=1,5
    C(M,N)=F(M,N)
    63 D(M,N)=G(M,N)
    GO TO 90
54 DO 64 M=1,25
    DO 64 N=1,5
    C(M,N)=G(M,N)
    64 D(M,N)=H(M,N)
    GO TO 90
55 DO 65 M=1,25
    DO 65 N=1,5
    C(M,N)=H(M,N)
    65 D(M,N)=P(M,N)
    GO TO 90
56 DO 66 M=1,25
    DO 66 N=1,5
    C(M,N)=P(M,N)
    66 D(M,N)=R(M,N)
    GO TO 90
57 DO 67 M=1,25
    DO 67 N=1,5
    C(M,N)=R(M,N)
    67 D(M,N)=S(M,N)
    GO TO 90
58 DO 68 N=1,25
    DO 68 N=1,5
    C(M,N)=S(M,N)
    68 D(M,N)=T(M,N)
    GO TO 90
59 DO 69 M=1,25
    DO 69 N=1,5
    C(M,N)=T(M,N)
    69 D(M,N)=U(M,N)
    GO TO 90
70 DO 80 M=1,25
    DO 80 N=1,5

```

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```
C(M,N)=U(M,N)
80 D(M,N)=V(M,N)
GO TO 90
71 DO 81 M=1,25
DO 81 N=1,5
C(M,N)=V(M,N)
81 D(M,N)=W(M,N)
GO TO 90
72 DO 82 M=1,25
DO 82 N=1,5
C(M,N)=W(M,N)
82 D(M,N)=Y(M,N)
GO TO 90
73 DO 83 M=1,25
DO 83 N=1,5
83 C(M,N)=Y(M,N)
LL=0
90 II=1
DO 50 I=1,25
IF(TIME(II)-Z(L)) 25,25,50
25 IF(LL) 35,35,30
30 IF(C(L,1),GE.0.01*C(L,5))GO TO 32
FRAC=(SQRT(A)-SQRT(X(I-1)))/(SQRT(X(I))-SQRT(X(I-1)))
GO TO 33
32 FRAC=(A-X(I-1))/(X(I)-X(I-1))
33 DO 34 J=1,5
34 C(L,J)=C(L,J)+FRAC*(D(L,J)-C(L,J))
35 RTIM=TM*Z(L)
PRINT 202,Z(L),RTIM
202 FORMAT(1H0,2X,42H TEMPERATURES FOR A DIMENSIONLESS TIME OF ,F5.2,
130X,6H TIME=,F6.3,7HSECONDS)
DO 40 J=1,5
40 TEMP(J)=C(L,J)*DEM-TI
PRINT 203,(B(J),J=1,5)
203 FORMAT(1H0,8X,12H DEPTH(CM.)=,5F9.2)
PRINT 204,(TEMP(J),J=1,5)
204 FORMAT(1H ,3X,17H TEMPERATURE( C)=,5F9.2)
50 CONTINUE
GO TO 1
100 CONTINUE
STOP
END
```

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```

PROGRAM KOTCYL (INPUT,OUTPUT)
DIMENSION X(9),Y(5),W(12),Z(24),R(5),C(24,12,5)D(24,12,5),E(24,12
1.5),P(24,12,5),TIME(24),TEMP1(5),TEMP2(5)
DATA X/.010,.025,.050,.100/
DATA Y/0.95,0.90,0.80/
DATA W/0.,30.,60.,90.,120.,150.,180.,210.,240.,270.,300.,330./
DATA Z/0.5,0.75,1.0,1.2,1.4,1.6,1.8,2.0,2.2,2.5,2.8,3.25,4.00,5.0,
+6.0,7.0,8.0,9.0,10.0,11.0,12.0,14.0,16.0,20.0/
1000 READ 1001,XK,RHO,CP,TM,RI,RO,TI,KK,I,J,N
1001 FORMAT(7F10.4,2(13,12))
IF(N.EQ.0)GO TO 2
11 I(XK) 129,120,1100
1100 READ 1002,QT,ABSR,(TIME(M),M=1,N)
1002 FORMAT(2E10.4,12F5.2/13F5.2)
502 FORMAT(1H0,2X,56H DIMENSIONLESS TEMPERATURES FOR A DIMENSIONLESS T
1IME OF ,F5.2,30X,6H TIME=,F6.3,7HSECONDS)
503 FORMAT(1H0,11H CYL ANGLE=,F4.0,3HDEG,3X,5HT* =,5F7.4,5X,10HCYL AN
GLE=,F4.0,3HDEG,2X,5HT* =,5F7.4)
504 FORMAT(1H ,21X,5HR/RO=,5F7.4,24X,5HR/RO=,5F7.4)
505 FORMAT(1H ,21X,5HT(C)=,5F7.1,24X,5HT(C)=,5F7.1)
GO TO 5
2 IF(XK) 120,120,7
7 READ 1002,QT,ABSR
DO 4 M=1,24
4 TIME(M)=A(M)
N1=24
5 ALPHA=XK/(RHO*CP)
A=ALPHA*TM/(RO*RO)
B=RI/RO
PRINT 401,A,B
401 FORMAT(91H1,31H, BASIC DIMENSIONLESS PARAMETERS,20X,5HBCYL=,F7.6,
15X,6HRI/RO=,F4.3)
PRINT 402,XK,RHO,CP
402 FORMAT(1H ,28H MATERIAL THERMAL PROPERTIES,4X,21HTHERMAL CONDUCTIV
1ITY=,F6.3,12HCAL/SEC-CM-C,4X,8HDENSITY=,F5.2,7HGMS/CM3,4X,14HSPECI
2FIC HEAT=,F4.3,8HCAL/GM-C)
PRINT 403,TM,QT
403 FORMAT(1H,31H WEAPON THERMAL CHARACTERISTICS, 10X,23HTIME TO MAX I
IRRADIANCE=,F7.4,7HSECONDS,9X,23HTOTAL RADIANT EXPOSURE=,F8.2,7HCAL
2/CM2)
PRINT 404,RI,RO,TI
404 FORMAT(1H,27X,13HINNER RADIUS=,F6.3,11HCENTIMETERS,4X,13HOUTER RA
LDIUS=,F6.3,11HCENTIMETERS,4X,20HINITIAL TEMPERATURE=,F5.1,5HDEG-C)
IZ=0
HM=QT/(2.6*TM)
DEM=ABSR*HM*RO/XK
R(1)=B
S=(1.0-B)/4.0
DO 3 K=2,5
K1=K-1

```

Figure 4. Computer Program to Obtain the Temperature Distribution History in Circular Cylinders Rotating at 6 rpm.

```

3 R(K)=R(K)+S
45 GO TO (50,60,70,60,60,70,60)KK
50 READ 1, (((E(K1,K2,K3),K1=1,24),K2=1,12),K3=1,5)
1 FORMAT(8F10.7)
GO TO 88
60 DO 21 K3=1,5
DO 21 K2=1,12
21 READ 1, (C(K1,K2,K3),K1=1,24)
DO 22 K3=1,5
DO 22 K2=1,12
32 READ 1, (D(K1,K2,K3),K1=1,24)
IF (KK-4) 88,80,80
70 READ 1, (((C(K1,K2,K3),K1=1,24),K2=1,12),K3=1,5)
READ 1, (((E(K1,K2,K3),K1=1,24),K2=1,12),K3=1,5)
GO TO 88
80 READ 1, (((E(K1,K2,K3),K1=1,24),K2=1,12),K3=1,5)
READ 1, (((F(K1,K2,K3),K1=1,24),K2=1,12),K3=1,5)
88 II=1
DO 110 L=1,24
IF (TIME(II)-Z(L)) 90,90,110
90 GO TO (108,91,98,98,98,98)KK
91 IF (C(L,1,1).GE.0.01*C(L,1,5))GO TO 92
FRAC=(SQRT(A)-SQRT(X(I-1)))/(SQRT(X(I))-SQRT(X(I-1)))
GC TO 93
92 FRAC=(A-X(I-1))/(X(I)-X(I-1))
93 J1=L
DO 94 J2=1,12
DO 94 J3=1,5
94 E(J1,J2,J3)=C(J1,J2,J3)+FRAC*(D(J1,J2,J3)-C(J1,J2,J3))
GO TO 108
98 IF (C(L,1,1).LE.0.01*C(L,1,5))GO TO 96
F1=1.0/(1.0-Y(J))
JK=J-1
F2=1.0/(1.0-Y(JK))
FB=1.0/(1.0-B)
FRAC=(FB-F1)/(F2-F1)
J1=L
DO 99 J2=1,12
DO 99 J3=1,5
99 E(J1,J2,J3)=E(J1,J2,J3)+FRAC*(C(J1,J2,J3)-E(J1,J2,J3))
R(1)=B
S=(1.0-B)/4.0
DO 33 J1=2,5
33 R(J1)=R(J1-1)+S
IF (KK-4) 35,100,35
35 IF (KK-5) 36,100,36
36 IF (KK-7) 108,100,108
96 S=(1.0-Y(J))/4.0
R(1)=Y(J)
DO 97 J1=2,5
97 R(J1)=R(J1-1)+S
R(1)=B
IF (KK-4) 108,100,100

```

```

100 IF(NK=6) 41,103,41
41 IF(D(L,1,1).LE.0.C1*D(L,1,5))GO TO 102
J1=L
DO 101 J2=1,12
DO 101 J3=1,5
101 F(J1,J2,J3)=F(J1,J2,J3)+FRAC*(D(J1,J2,J3)-F(J1,J2,J3))
102 IF(E(L,1,1).GE.0.01*E(L,1,5))GO TO 103
FRAC=(SQRT(A)-SQRT(X(I-1)))/(SQRT(X(I))-SQRT(X(I-1)))
GO TO 104
103 FRAC=(A-X(I-1))/(X(I)-X(I-1))
104 J1=L
DO 105 J2=i,12
DO 105 J3=1,5
105 F(J1,J2,J3)=E(J1,J2,J3)+FRAC*(F(J1,J2,J3)-E(J1,J2,J3))
106 RTIM=TM*Z(L)
PRINT 502,Z(L),RTIM
M=1
DO109 IK=1,6
IZ=IZ+1
M1=M+1
PRINT 503,W(M),E(L,M,K),K=1,5),W(M1),(E(L,M1,K),K=1,5)
DO111 K=1,5
TEMP1(K)=E(L,M,K)*DEM+TI
111 TEMP2(K)=E(L,M1,K)*DEM+TI
PRINT 505,(TEMP1(K),K=1,5),(TEMP2(K),K=1,5)
PRINT 504,(R(K),K=1,5),(R(K),K=1,5)
M=M+2
109 CONTINUE
IF(IZ=12) 131,130,130
130 IZ=0
PRINT 509
509 FORMAT(1H1.//)
131 CONTINUE
II=II+1
IF(II=N1) 110,110,115
110 CONTINUE
115 GO TO 1000
120 CONTINUE
STOP
END

```

MOLTR 72-177

```
PROGRAM THINEL (INPUT,OUTPUT)
DIMENSION T(30),Q(30),TEMP(30),TIME(30)
DATA T/0.0,0.5,0.75,1.0,1.2,1.4,1.6,1.8,2.0,2.2,2.5,2.8,3.25,4.0,
+5.0,6.0,7.0,8.0,9.0,10.0,12.5,15.0,20.0,30.0,40.0,50.0/
DATA Q/0.0,.037,.109,.203,.279,.347,.400,.422,.477,.507,.545,.577
+.617,.668,.714,.748,.773,.793,.810,.824,.849,.874,.902,.934,.952,.
+.964/
1 READ 100,RHO,CP,TM,THICK,TL,QT,ABSR
100 FORMAT(7F10.4)
    IF(RHO) 75,75,2
2 DEM=RHO*CP*THICK
    DO 20 K=1,26
20 TIME(K)=T(K)*TM
    PRINT 200
200 FORMAT(1H, 74H THERMALLY-THIN ELEMENTS AVERAGE TEMPERATURE HIS
1 STORY BY ENERGY BALANCE)
    PRINT 201,RHO,CP,THICK
201 FORMAT(1H0,11H DENSITY=,F6.3,7HGMS/CM3,14H SPEC. HEAT=,F5.3,
112HCAL/CM-SEC-D,15H WALL THICK.=,F6.3,3HCM.)
    PRINT 403,TM,QT
403 FORMAT(1H ,31H WEAPON THERMAL CHARACTERISTICS, 3X,23HTIME TO MAX I
1RRADIANCE=,F6.4,7HSSECONDS,4X,23HTOTAL EXPOSURE=,F6.2,7HCAL
2/CM2)
    DO 10 K=1,26
10 TEMP(K)=Q(K)*QT/DEM+TI
    PRINT 204,(T(L),L=1,14)
204 FORMAT(1H0,12H T/TMAX=,14F7.2)
    PRINT 205,(TIME(L),L=1,14)
205 FORMAT(1H, 12H TIME(SEC)=,14F7.3)
    PRINT 206,(TEMP(L),L=1,14)
206 FORMAT(1H ,12H TEMP( C)=,14F7.1)
    PRINT 207,(T(L),L=15,26)
207 FORMAT(1H0,16X,10H T/TMAX=,12F7.2)
    PRINT 208,(TIME(L),L=15,26)
208 FORMAT(1H ,16X,10HTIME(SEC)=,12F7.3)
    PRINT 209,(TEMP(L),L=15,26)
209 FORMAT(1H, 16X,10H TEMP( C)=,12F7.1)
    GO TO 1
75 CONTINUE
    STOP
END
```

Figure 5. Computer Program to Obtain the Temperature History in Thermally-Thin Elements

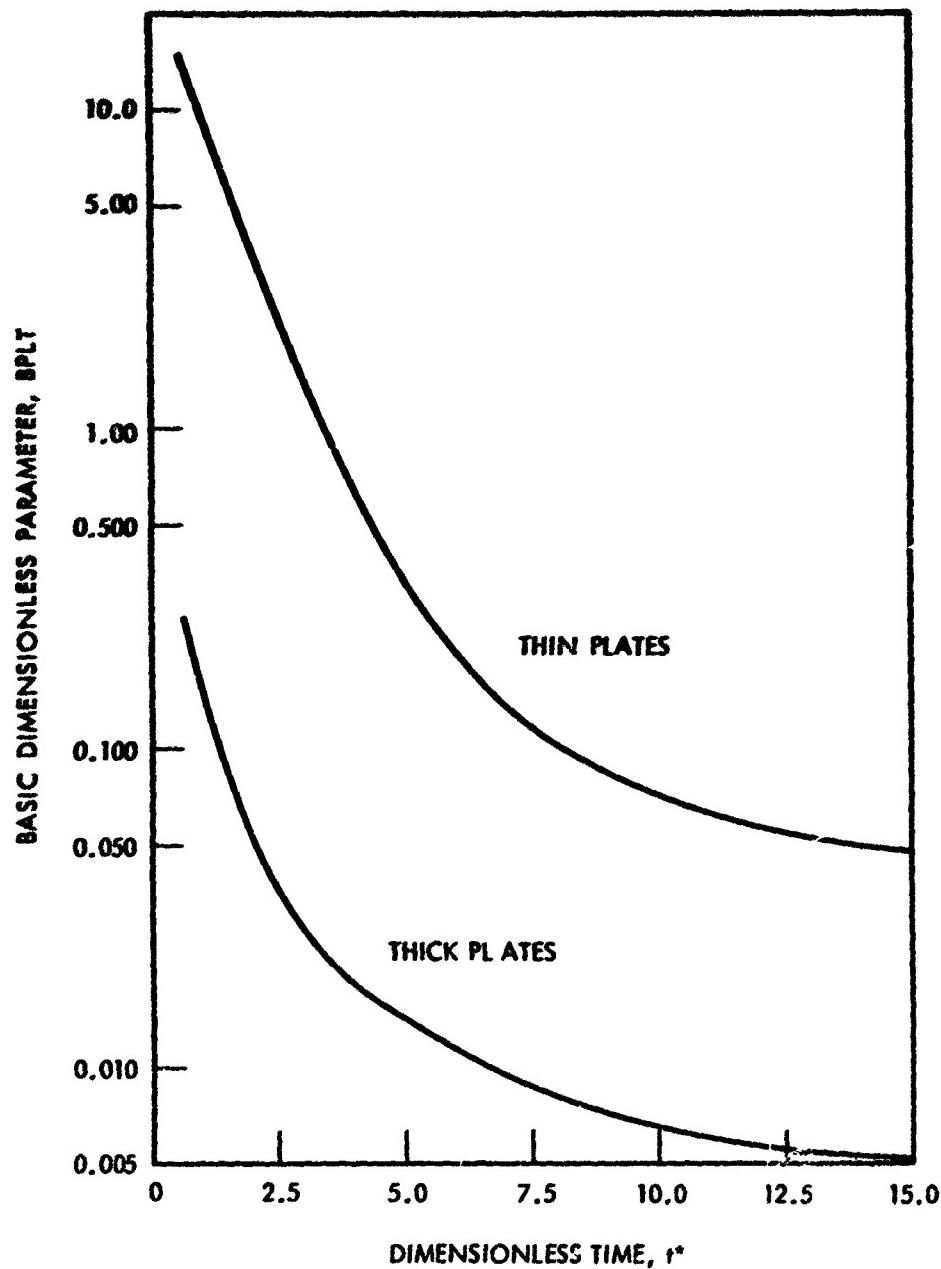


FIG. 6 THERMALLY-THICK AND THERMALLY-THIN REGIONS OF A PLATE EXPOSED TO THE THERMAL RADIATION PULSE OF A NUCLEAR WEAPON.

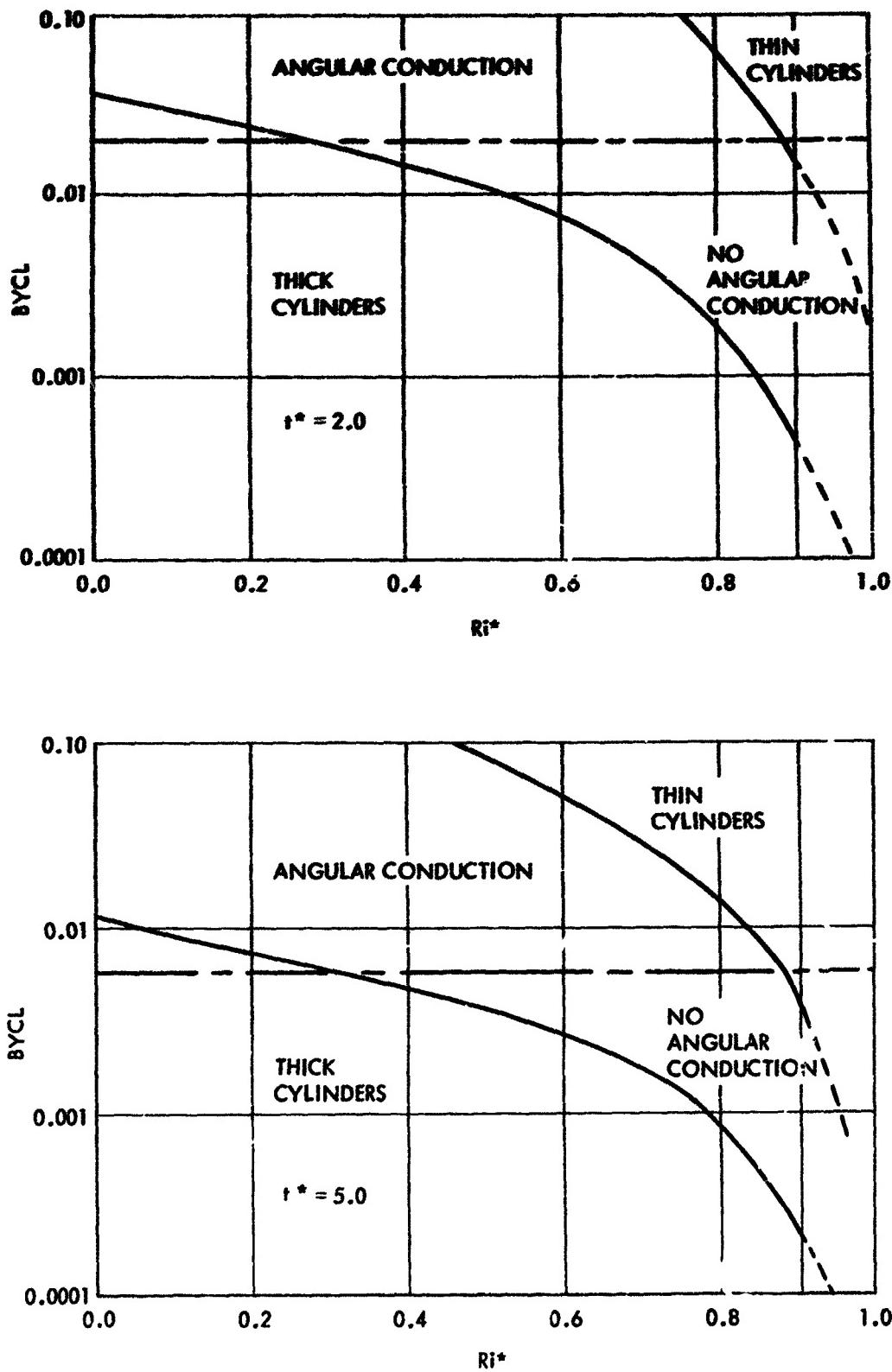


FIG. 7 THERMAIN-THICK AND THERMAIN-THIN REGIONS OF A CIRCULAR CYLINDER EXPOSED TO THE THERMAL RADIATION PULSE OF A NUCLEAR WEAPON

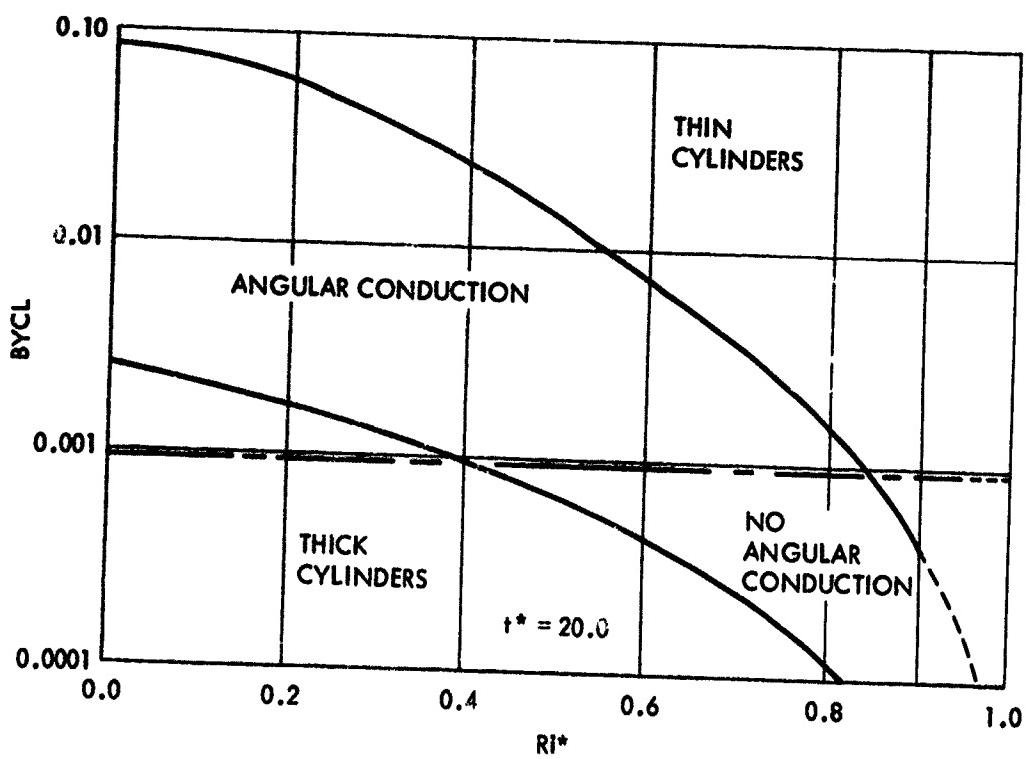
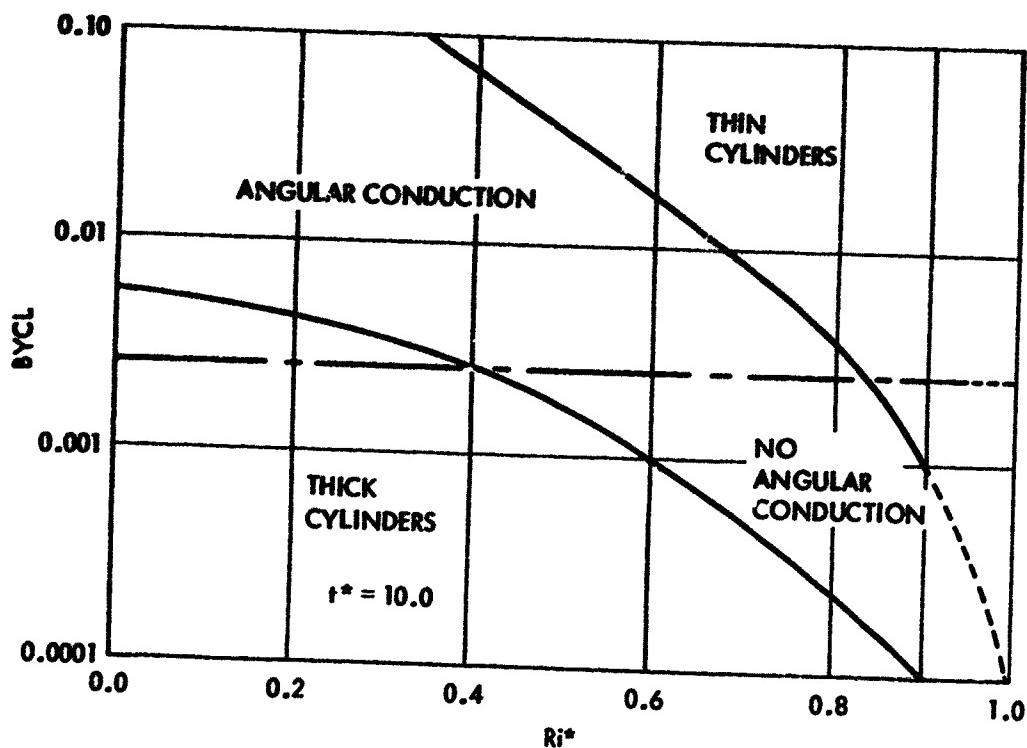


FIG. 7 (CONTINUED)

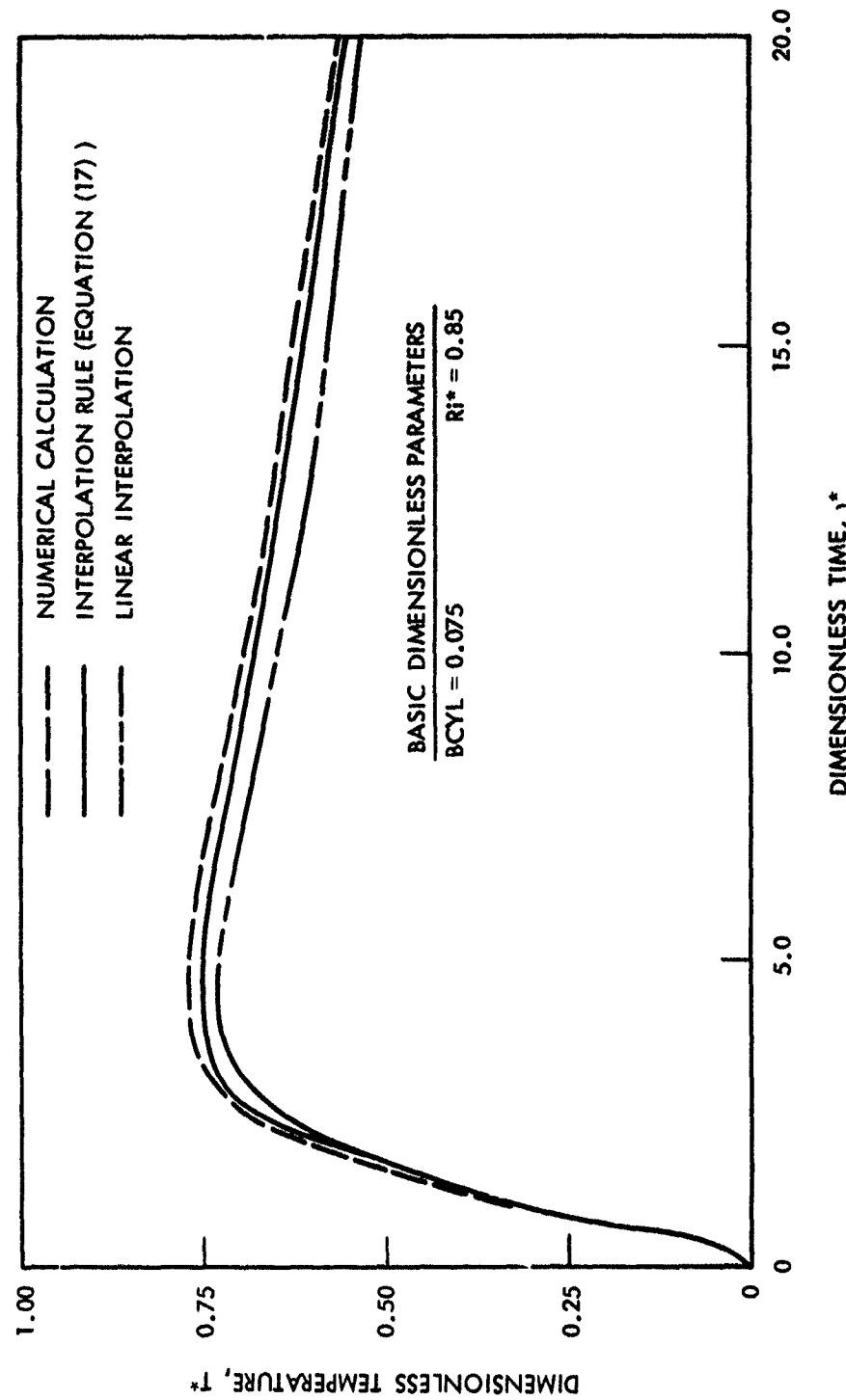


FIG. 8 COMPARISON OF THE SURFACE TEMPERATURE ON A STATIONARY CIRCULAR CYLINDER AS GENERATED BY A NUMERICAL CALCULATION AND BY THE INTERPOLATION RULES.

## APPENDIX A

## HEAT TRANSFER EQUATIONS AND BOUNDARY CONDITIONS

The heat conduction equation is the governing partial differential equation which determines the temperature distribution history in the structural elements of this report. These elements are heated by the nuclear weapon thermal radiation pulse only and no heat is removed at any surface. Also, these structural elements are assumed to be constructed of isotropic, homogeneous materials whose thermophysical properties are constant. Following is a mathematical statement of the thermal radiation heating problem for each of the four structural elements, consisting of the heat conduction equation and appropriate boundary conditions.

## (1) Plates

$$K \frac{\partial^2 T}{\partial X^2} = \rho \text{ cp } b \frac{\partial T}{\partial t} \quad (\text{A-1})$$

$$X=0 \quad -K \frac{\partial T}{\partial X} = H \quad (\text{A-2})$$

$$X=b \quad \frac{\partial T}{\partial X} = 0 \quad (\text{A-3})$$

## (2) Circular Cylinders

$$\frac{K}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{K}{r^2} \frac{\partial^2 T}{\partial \theta^2} = \rho \text{ cp } \frac{\partial T}{\partial t} \quad (\text{A-4})$$

$$r=R_o \quad -K \frac{\partial T}{\partial r} = \begin{cases} AH \cos \theta & \theta \leq \pm \pi/2 \\ 0 & \theta > \pm \pi/2 \end{cases} \quad (\text{A-5})$$

$$r=R_i \quad \frac{\partial T}{\partial r} = 0 \quad (\text{A-6})$$

## (3) Rotating Circular Cylinders

$$\frac{K}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{K}{r^2} \frac{\partial^2 T}{\partial \theta^2} = \rho c p \frac{\partial T}{\partial t} \quad (A-7)$$

$$r=R_o \quad -K \frac{\partial T}{\partial r} = \begin{cases} AH \cos(\theta+\omega t) & \cos(\theta+\omega t) > 0 \\ 0 & \cos(\theta+\omega t) < 0 \end{cases} \quad (A-8)$$

$$r=R_i \quad \frac{\partial T}{\partial r} = 0 \quad (A-9)$$

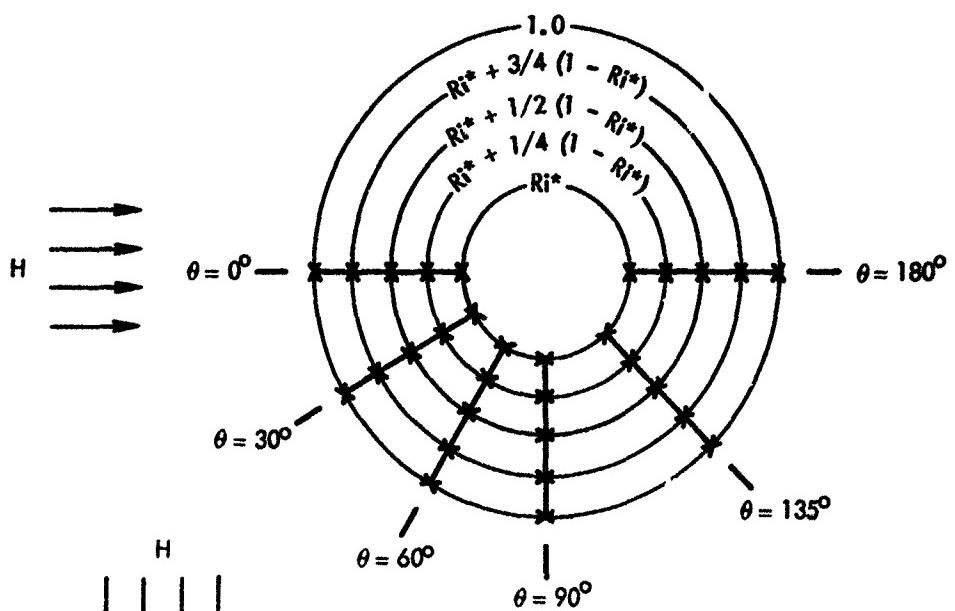
Note that  $\omega = \pi/5$  radians/sec (6 rpm) only in this report.

## (4) Thermally-Thin Elements

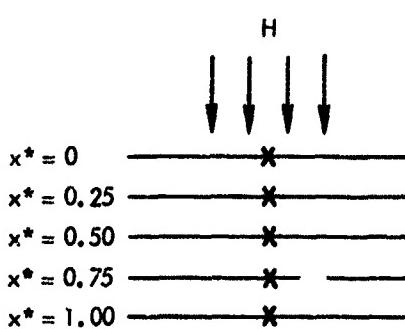
$$\rho c p b \frac{\partial T}{\partial t} = AH \quad (A-10)$$

Figure (A-1) is a schematic diagram of each of the four structural elements of this report. Also shown are the positions on the element for which temperature has been calculated by solving the appropriate heat conduction equation described above.

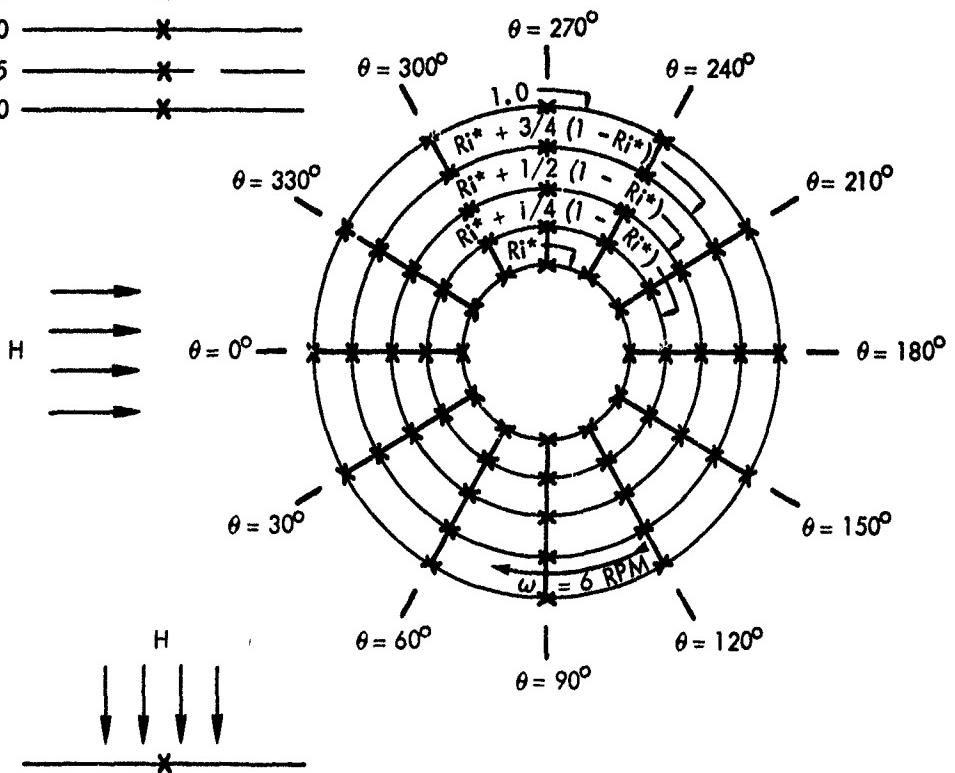
STATIONARY  
CIRCULAR  
CYLINDERS



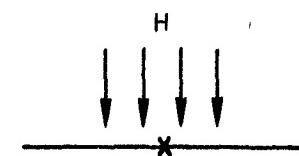
FLAT  
PLATES



ROTATING  
CIRCULAR  
CYLINDERS



THERMALLY-  
THIN  
ELEMENT



X POSITIONS FOR WHICH TEMPERATURES ARE GIVEN

FIG. A-1 POSITIONS ON THE STRUCTURAL ELEMENTS FOR WHICH TEMPERATURES HAVE BEEN CALCULATED

## APPENDIX B

## DEFINITION OF VARIABLES REQUIRED TO RUN THE COMPUTER PROGRAMS

The variables used in the four computer programs of this report have common definitions and use common systems of units. Two possible systems of units may be used. If temperatures in degrees Centigrade are desired, all variables are given in c.g.s. units and calories. If degrees Fahrenheit are wanted, the corresponding input variable units are inches, seconds and BTU. The following is a list of definitions for all of the variables required to run any of the four computer programs.

Floating Point Variables

ABSR	Absorptance of target material
CP	Material specific heat
XK	Material thermal conductivity
RI	Inner radius of the circular cylinders
RHO	Material density
RO	Outer radius of the circular cylinders
TI	Initial temperature
TIME	Dimensionless time values for which the temperature history is to be calculated, (chosen from the allowable values of Table 1)
THICK	Plate thickness
TM	Time at which maximum thermal irradiance occurs
QT	Total radiant exposure per unit area

Fixed Point Variables

I	Number indicating the value of BCYL for rotating cylinders (see description of program ROTCYL)
J	Number indicating the value of Ri* for rotating cylinders (see description of program ROTCYL)
KK	Number indicating the manner of interpolation or extrapolation of circular cylinder data (see description of program ROTCYL)

---

\* The user is cautioned that the headings on the computer outputs are always in c.g.s. units, calories and degrees centigrade.

## APPENDIX C

## EXAMPLES FOR THE SET-UP AND USE OF THE COMPUTER PROGRAMS

This section presents examples showing how each of the computer programs of this report are set-up and run. The output of each program will also be described and part of the solutions presented in graphical form. A single target element will be analyzed by each program in turn. It was chosen such that the results of each program can be compared to show when these solutions are in agreement. Figures 6 and 7 which indicate where heat conduction effects become important will be referred to, to explain why these programs can yield the same result. The common target element is composed of aluminum which has the following thermal properties: Thermal conductivity = 0.374 cal/sec-cm-°C, Density = 2.71 gms/cm<sup>3</sup>, and Specific Heat = 0.23 cal/gm-°C. (Thermal Diffusivity = 0.60 cm<sup>2</sup>/sec). This element is normally exposed to a nuclear weapon detonation such that the time to maximum irradiance is 1.0 second and is at a separation distance from the explosion such that the total radiant exposure is 100 cal/cm<sup>2</sup>. The element initial temperature is 20°C and its absorptance is 1.0.

(1) Temperature Distribution History in a Stationary Circular Cylinder (Program CYLDAT)

A cylindrical target element of outer radius 6.33 centimeters and inner radius 5.38 centimeters is exposed to the nuclear weapon detonation described above. Two data input cards plus the magnetic tape containing the dimensionless temperature data are required to run this program. The following is a table of the numbers required and their location on the input cards. The corresponding variables were specified in the Description and Use of Computer Programs section and were defined in Appendix A.

	Card	Column	Number						
		10	20	30	40	50	60	70	80
Card 1	0.374	2.71	0.230	1.0	5.38	6.33	20.0	0	
Card 2	100.0		1.0						

For this input, the program computes and prints out the values of BCYL and RI\* (0.015 and 0.85, respectively). The values of the material thermophysical properties ( $k$ ,  $\rho$ , and  $c_p$ ), the weapon thermal pulse characteristics ( $t_m$  and  $Q_T$ ) and the cylinder radii are also printed. Subsequently, the temperature history is retrieved and printed in dimensional and dimensionless form for the 24 selected

values of time, the eight selected values of cylinder angle and the five allowable values of cylinder radius (see Table 1). Figure B-1 is a plot of part of the results generated by the program in solving this problem.

### (2) Temperature History in a Plate (Program PLT1D)

A target element consisting of a plate 0.95 centimeters thick is exposed to the same nuclear weapon detonation as in the previous example. Note that this plate has the same thickness as the stationary circular cylinder. Two data input cards are required to run this program. The following is a table of the numbers and their location on the data input cards. The corresponding variables were specified in the Description and Use of Computer Programs section and were defined in Appendix A.

	Card	Column	Number				
	10	20	30	40	50	60	70
Card 1	0.374	2.71	0.230	1.0	0.95	20.0	0
Card 2	100.0		1.0				

For this input, the program prints the value of BPLT and the plate thickness. The values of the thermophysical properties ( $k$ ,  $\rho$ , and  $c_p$ ) and the thermal pulse characteristics ( $t_m$  and  $Q_T$ ) are also printed. Subsequently the temperature history is retrieved and printed for the 25 selected values of time and the five selected values of distance into the plate. Figure B-2 is a plot of part of the results generated by the program in solving this problem.

A comparison of figures B-1 and B-2 shows that the temperature history of the circular cylinder at its most forward point ( $\theta=0^\circ$ ) is similar to that of the plate with identical thickness. This result could have been predicted by referring to Figure 7. That is, for the values of BCYL and  $Ri^*$  of this problem (.015 and 0.85), Figure 7 shows that angular conduction is negligible for  $t^*$  values up to 2.0. A  $t^*$  of 2.0 corresponds to 2.0 seconds of real time for this problem. When angular (circumferential) heat conduction is small, the most forward cylinder point and the plate will have similar temperature histories. As angular conduction increases with time, more heat is conducted away from the most forward point and its temperature history departs from that of a plate.

### (3) Temperature Distribution History in a Rotating Circular Cylinder (Program ROTCYL)

The cylindrical target element of example (1) is rotating at six revolutions per minute and is exposed to the same nuclear weapon detonation. Before this program can be run it is first necessary to compute the values of the parameters BCYL and  $Ri^*$ . Values of 0.015 and 0.85 are found for these variables. Next, these values must be inspected to determine if interpolation or extrapolation of the dimensionless temperature data is required. An inspection shows

that interpolation on both BCYL and  $Ri^*$  is required (see Table 1 for selected values). Furthermore, KK, the number indicating the manner of the interpolation is four (see Table under Description and Use of the Computer Programs). Finally, the dimensionless temperature decks must be selected and the numbers I and J indicating these decks specified. I indicates the nearest larger value of BCYL and J the nearest smaller value of  $Ri^*$  hence I is two and J is three for this case (allowable values of I and J are specified in Description and Use of the Computer Programs). Some double interpolation is needed in this problem, four dimensionless temperature data decks are input in addition to the two data input cards. The following is a table of the numbers required and their location on the input cards. The corresponding variables were specified in the Description and Use of Computer Programs section and were defined in Appendix A.

	Card	Column	Number
Card 1		10      20      30      40      50      60      70      73      75      78      80	0.374    2.71    0.230    1.0    5.38    6.33    20.0    4    2    3    0
Card 2		100.0    1.0	

Dimensionless Temperature Data Deck (I=1, J=3)

Dimensionless Temperature Data Deck (I=2, J=3)

Dimensionless Temperature Data Deck (I=1, J=2)

Dimensionless Temperature Data Deck (I=2, J=2)

For this input, the program prints the value of BCYL and  $Ri^*$ . The values of the material thermophysical properties ( $k$ ,  $\rho$ , and  $cp$ ), the weapon thermal characteristics ( $tm$  and  $QT$ ) and the cylinder radii are also printed. Subsequently, the temperature distribution history is retrieved and printed in dimensional and dimensionless form for the 24 selected values of time, the 12 allowable values of cylinder angle and the five selected values of cylinder radius (see Table 1). Figure B-3 is a plot of part of the results generated by the program in solving this problem.

Figures B-1 and B-3 can be compared to show the effect of cylinder rotation on temperature distribution history. It is seen that rotation causes great changes by (1) lowering the maximum temperatures (2) decreasing the temperature gradients in the circumferential direction and (3) causing the maximum temperatures to occur at a cylinder angle of  $30^\circ$  instead of at the most forward point. A comparison of these figures with Figure (B-2) shows that the temperature history of the most forward point of cylinders and the plate are similar for only the first second of heating. Thus, the region of negligible angular conduction shown in Figure 6 for a stationary cylinder has been reduced to approximately one second by the 6 rpm rotation. Also, it can be deduced from the figures that rotation causes a much greater departure from the temperature history for no angular conduction than a movement into the angular conduction region.

## (4) Temperature History in a Thermally-Thin Element (Program THTEL)

A target element 0.95 centimeters thick is exposed to the nuclear weapon detonation of the previous examples. Note that this element can represent either the plate or cylindrical element of examples (1) and (2). Only one data input card is required to run this program. The following is a table of numbers and their location on the data input card. The corresponding variables were specified in the Description and Use of Computer Programs section and were defined in Appendix A.

	Card	Column	Number
		10      20      30      40      50      60      70	
Card 1	2.71    0.230	1.0      0.95      20.0      100.0      1.0	

For this input, the program prints the values of the material thermophysical properties ( $\rho$ ,  $c_p$ , and  $k$ ), the weapon thermal pulse characteristics ( $t_m$  and  $Q_T$ ) and the element thickness. Subsequently, the average temperature history is computed and printed for the 26 selected values of time (see Table 1). Figure B-4 is a plot of the results generated by this program.

A comparison of Figures B-2 and B-4 shows that the temperature history of the plate and the thin element are very similar for large values of time. This result could have been predicted by Figure 6. That is, Figure 6 predicts that the plate is thermally-thin for dimensionless time values greater than 3.5 (greater than 3.5 seconds in these examples). A comparison of Figures B-1 and B-4 shows that the temperature history of the most forward point on the circular cylinder and the thin element are similar for some intermediate values of time. This region of agreement could have been deduced from Figure 7 as the region where the cylinder is both thermally-thin and where angular conduction is negligible.

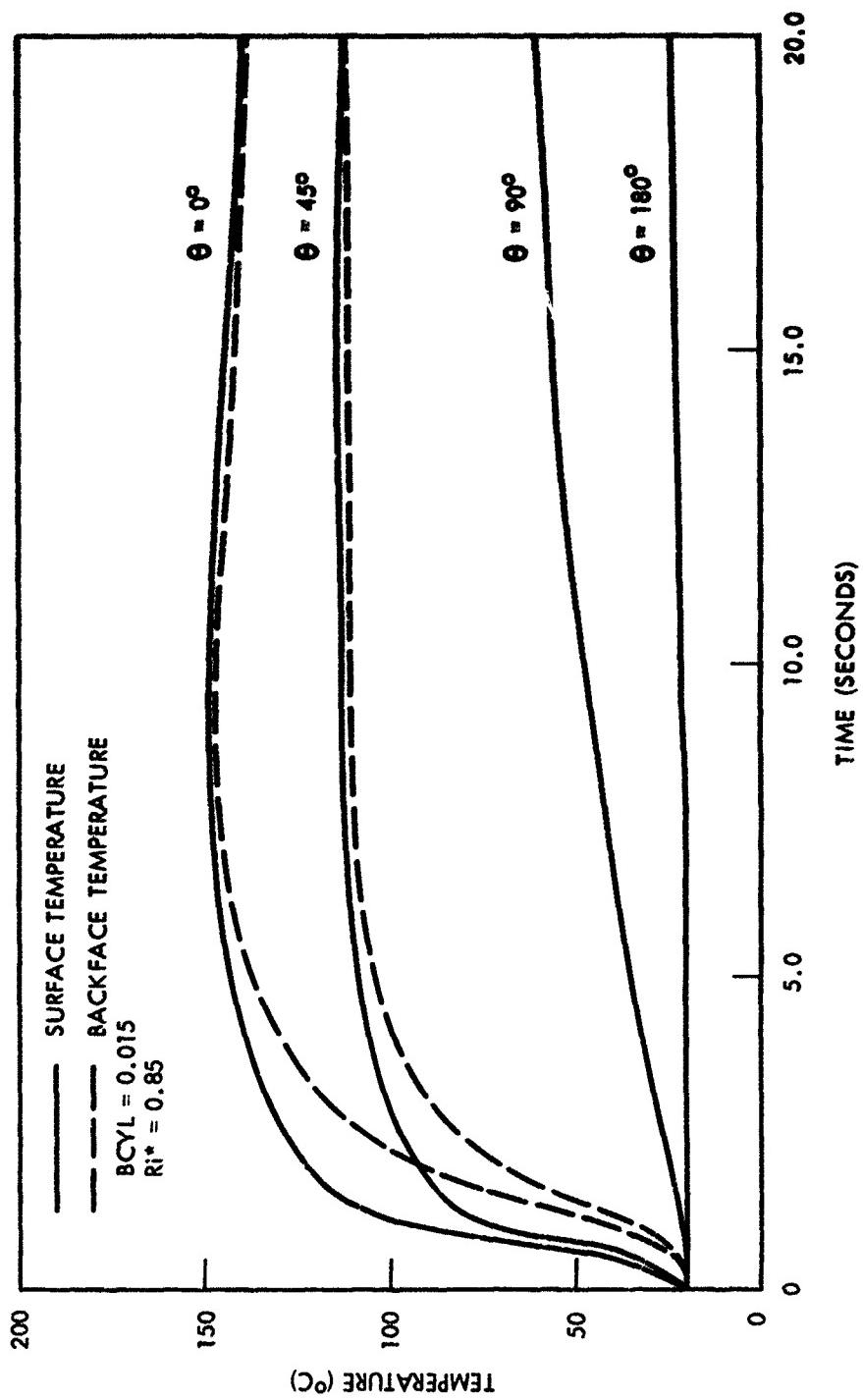


FIG. C-1 EXAMPLE OF THE TEMPERATURE DISTRIBUTION HISTORY IN A STATIONARY CIRCULAR CYLINDER.

C-5

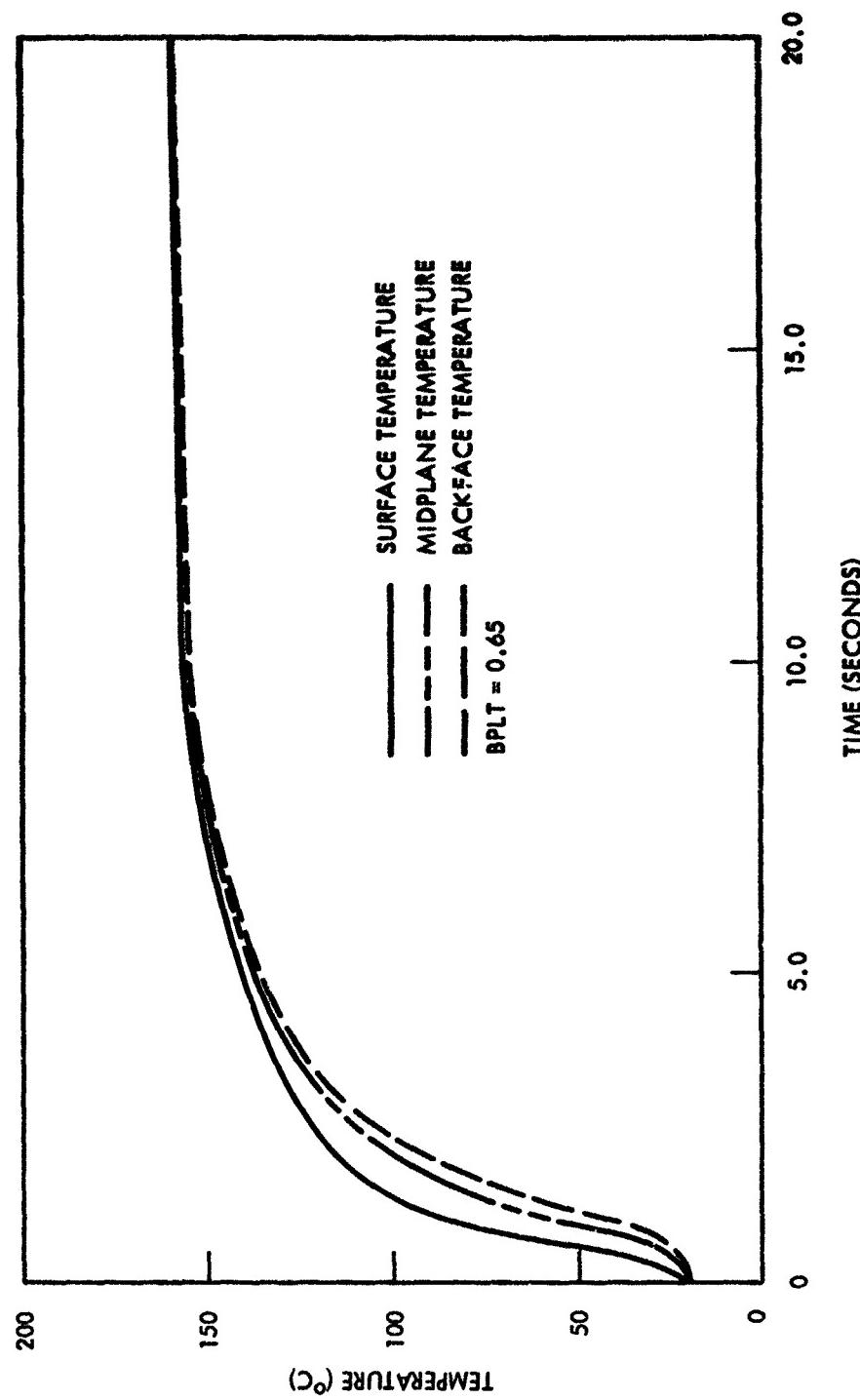
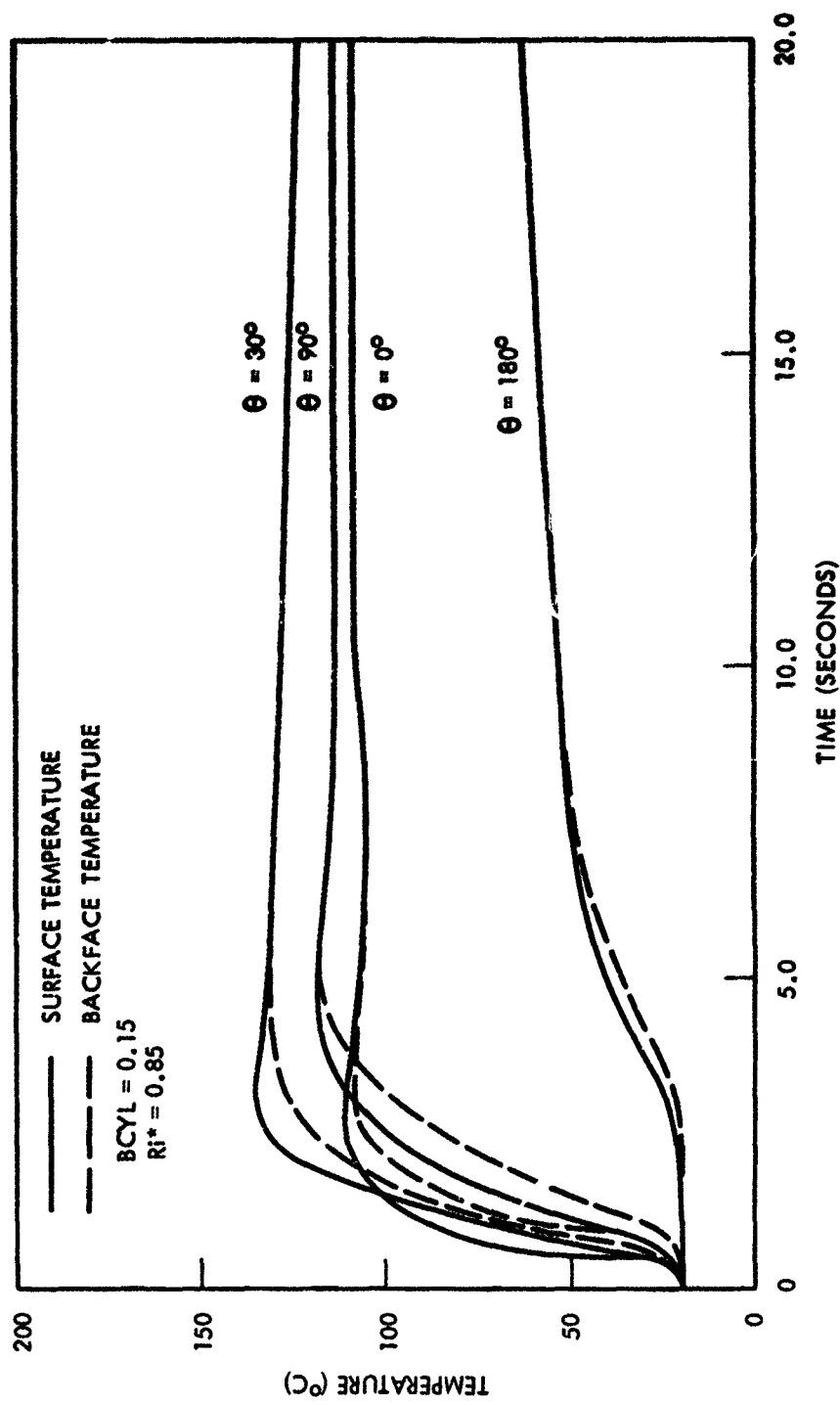


FIG. C-2 EXAMPLE OF THE TEMPERATURE DISTRIBUTION HISTORY IN A PLATE.

C-6



C - 7

FIG. C-3 EXAMPLE OF THE TEMPERATURE DISTRIBUTION HISTORY IN A CIRCULAR CYLINDER ROTATING AT 6 RPM.

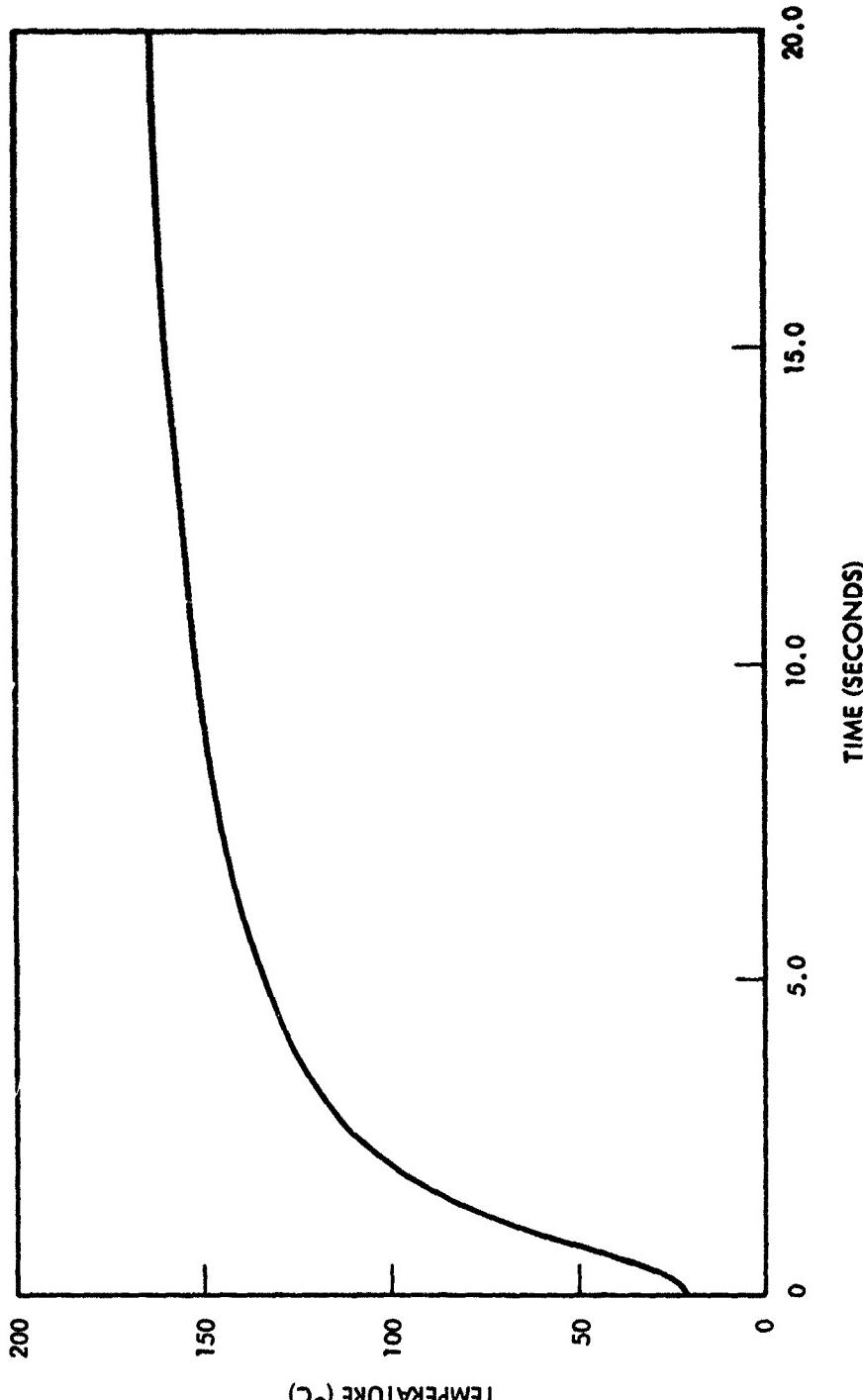


FIG. C-4 EXAMPLE OF THE AVERAGE TEMPERATURE HISTORY IN A THERMALLY-THIN ELEMENT.

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